CKM Physics

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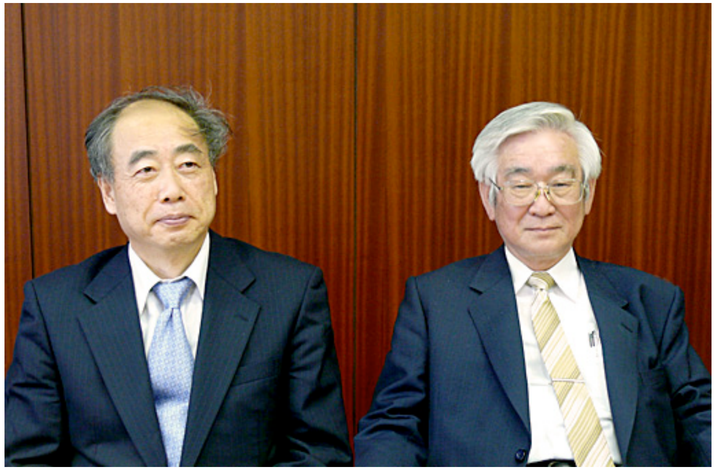
Outline

- Introduction
  - CKM and the Unitarity Triangle
  - Neutral meson mixing
  - CP Violation
- Experimental Test of CKM Theory
  - |Vij| measurements
  - CP Violation: UT phases measurement
  - Direct CP Violation
  - New Physics Searches
- Summary and Outlook

2008 Nobel Prize in Physics

N. **C**abibbo

Flavour Mixing
(1964)



M. **K**obayashi T. **M**askawa

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

3rd Generation
(1973)

(shared with Y. Nambu)

CKM Matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Unitary 3x3 matrix connecting flavour quark eigenstates to mass quark eigenstates
- Can be completely determined by 4 (observable) parameters including 1 irreducible complex phase giving rise to CPV

Parametrization due to Wolfenstein (1983) :

$$|V_{us}| = \lambda, \ |V_{cb}| = A \cdot \lambda^2, \quad \varphi = Arg(V_{ub}^* V_{ud} V_{cd}^* V_{cb})$$

$$|V_{ub}| \cdot \cos\varphi = A \cdot \lambda^3 \cdot \rho, \ |V_{ub}| \cdot \sin\varphi = A \cdot \lambda^3 \cdot \eta$$

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$\lambda \sim 0.22 = \sin\theta_c$

$A \sim 0.8$

$\rho \sim 0.2 - 0.27$

$\eta \sim 0.28 - 0.37$

$\eta \neq 0$ for CP Violation

Unitarity Triangle

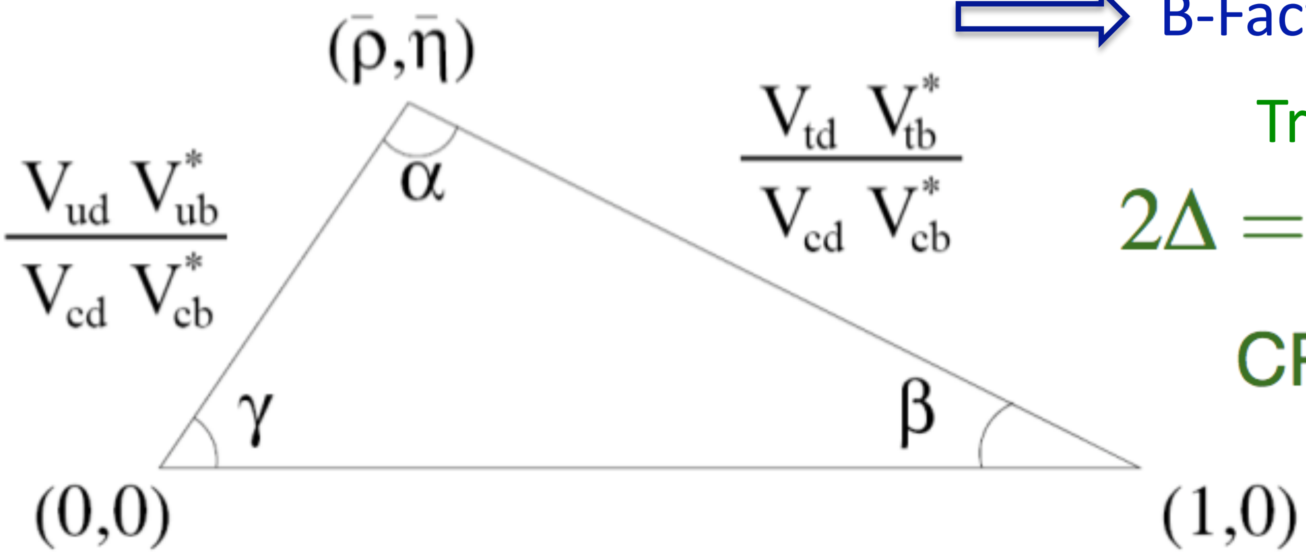
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity: $\sum_i V_{ij} V_{ik}^* = \delta_{jk}; \quad \sum_j V_{ij} V_{kj}^* = 0$

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

Unitarity relation for B_d decays

⇒ B-Factories ⇐



Triangle area:

$$2\Delta = J_{CP} \approx A^2 \lambda^6 \eta$$

$$\text{CPV} \leftrightarrow \eta \neq 0$$

The **ANGLES** are accessible to experiment via the measurement of the interference of different amplitudes (decay or mixing)

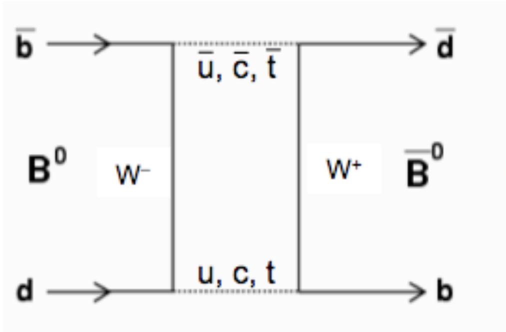
The **SIDES** are accessible to experiment via the measurements of decay amplitudes

Mixing

- Neutral B mesons oscillate between B^0 and $\overline{B}^0$. The Hamiltonian is

$$\begin{aligned}\mathbf{H} &= \mathbf{M} + \frac{i}{2}\mathbf{\Gamma} \\ &= \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} + \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}\end{aligned}$$

$\langle \overline{B}^0 | H | B^0 \rangle$ =



+ Long Distance Terms

- We study the mass eigenstates: $|B_{\mathrm{L,H}}\rangle = p\sqrt{1 \mp z}|B^0\rangle \pm q\sqrt{1 \pm z}|\overline{B}^0\rangle$
  - If CPT is conserved z=0
  - p and q are mixing parameters: $\frac{q}{p} = \sqrt{\frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}}}$
  - Physics depends on mass eigenstate differences in m and Γ:

$$\Delta m = m_{\mathrm{H}} - m_{\mathrm{L}} \qquad \Delta\Gamma = \Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}}$$

CP Violation

$$A_f \equiv A(M \to f); \quad \bar{A}_f \equiv A(\bar{M} \to f);$$
$$A_{\bar{f}} \equiv A(M \to \bar{f}); \quad \bar{A}_{\bar{f}} \equiv A(\bar{M} \to \bar{f});$$

$$|M_{H,L}\rangle = q|M^0\rangle \pm p|\bar{M}^0\rangle;$$

- There are three types of CPV:
  - CPV in decay (or direct) $CPV \Rightarrow \left|\frac{A(M \to f)}{A(\bar{M} \to \bar{f})}\right| \neq 1$
  - CPV in mixing $CPV \Rightarrow \left|\frac{q}{p}\right| \neq 1$
  - CPV in interference between decay and mixing:
    - Can occur if both M^0 and $\bar{M}^0$ decay to a common state f

$$M^0 \to f;$$
$$M^0 \to \bar{M}^0 \to f;$$

$$CPV \Rightarrow \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \neq 1 \qquad \frac{q}{p} = \left|\frac{q}{p}\right| \cdot e^{-i\cdot\Phi_{m(M)}}$$

Mixing phase

(B_d system)

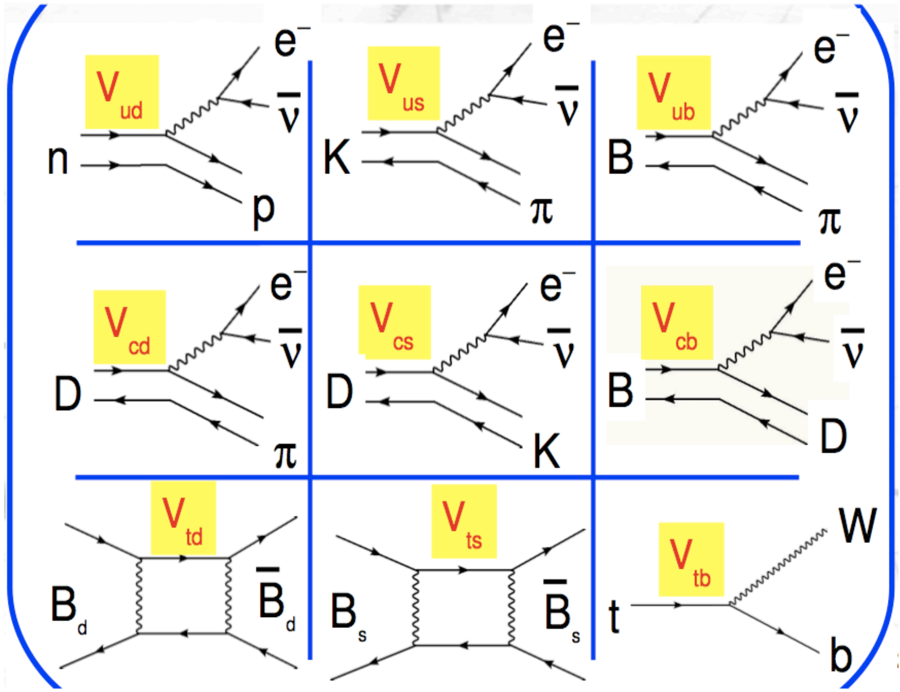
$$e^{-i\cdot\Phi_m} = \frac{(V_{tb}^* V_{td})}{(V_{tb} V_{td}^*)}$$

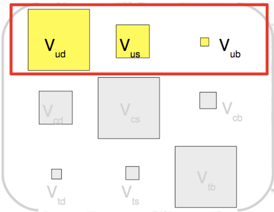
CKM Physics

- Put KM theory of CP violation to the test
  - Measure individual CKM matrix elements
    - |Vij| $\rightarrow$ decay rates
  - Observe and measure CPV
    - Completely determine the position of the UT vertex
      - This can be done **at B factories** by measuring the angles α,β,γ or the sides of the UT
  - Over-constrain the UT
    - measuring 3 or more of the observables (i.e. α+β+γ=π)
    - make independent measurements of the same observable with different processes (i.e. sin2β in b->c$\bar{c}$s with sin2β from b->c$\bar{c}$d, etc.)
  - Any statistically significant deviation from unitarity, or difference between measurements, may be due to new physics

$|V_{ij}|$: Amplitudes

- First Row
  - $|V_{ud}|$
    - Nuclear beta decays
  - $|V_{us}|$
    - K and τ decays (KLOE, BaBar, Belle)
  - $|V_{ub}|$
    - Charmless B decays (BaBar, Belle)
- Second Row
  - $|V_{cd}|,|V_{cs}|$
    - D decays (CLEO-c)
  - $|V_{cb}|$
    - B decays (BaBar, Belle)
- Third Row
  - $|V_{td}|,|V_{ts}|$
    - B_d , B_s Mixing (CDF, D0, BaBar, Belle)
  - $|V_{tb}|$
    - T decays (CDF, D0)





Towner, Hardy CKM 2008

First Row: $|V_{ud}|$

Best $|V_{ud}|$ measurement from super-allowed $0^+ \rightarrow 0^+$ nuclear β decay

$$ft = \frac{K}{G_V^2 \langle \tau_+ \rangle^2}$$

$$\mathcal{F}t = ft(1 + \delta'_R)(1 - (\delta_C - \delta_{NS})) = \text{constant}$$

Isospin corr.

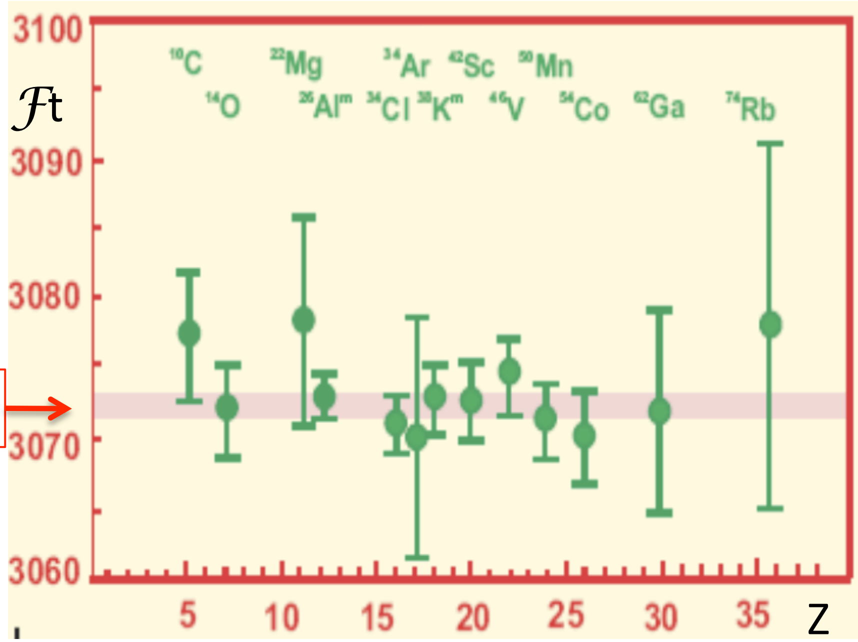
nucl. str

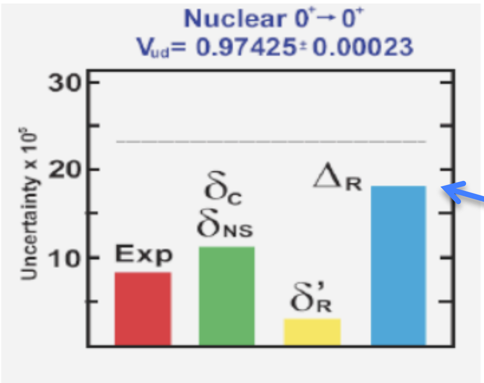
rad. corr

CVC

$$V_{ud}^2 = \frac{K}{2 G_F^2 \mathcal{F}t (1 + \Delta_R)} \qquad \frac{K}{(\hbar c)^6} = \frac{2\pi^3 \hbar \ln 2}{(m_e c^2)^5}$$

$\langle \mathcal{F}t \rangle = 3072.2 \pm 0.8$



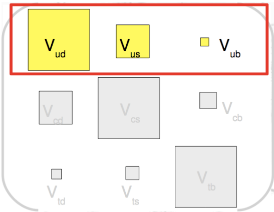


Dominated by theory error Δ_R

$V_{ud} = 0.97425 \pm 0.00023$

Review '05 : $V_{ud} = 0.97380(40)$

Sept '08 : $V_{ud} = 0.97425(23)$



First Row: $|V_{us}|$

- A precise measurement of V_{us} could allow a stringent test of unitarity of the CKM matrix opening a window on new physics

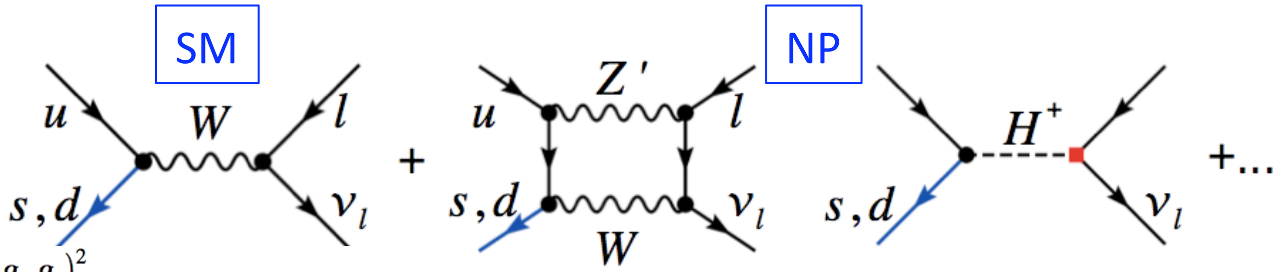
neglect $\approx 10^{-5}$

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=1$$

precisely known

The most precise unitarity test of V_{CKM} from 1st row

- New physics can introduce gauge breaking processes in the SM Lagrangian of charged current weak interactions of quarks

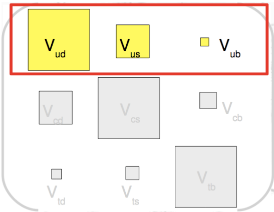


$$\frac{(g_q g_l)^2}{M_W^4}(|V_{ud}|^2+|V_{us}|^2)=G^2_{CKM}$$

[Marciano]

$$\mathrm{SM}+\mathrm{NP} \propto G_F^2|V_{uq}|^2\left(1+a\left(M_W/M_X\right)^2\right)^2, \text{naively } a_{\text{tree}}\sim 1,\ a_{\text{loop}}\sim g^2$$

V_{us} at 0.5%: $G_F = 1.16xx(4)$ $\Rightarrow M_{tree}\sim 5$ TeV, $M_{loop}\sim 1$ TeV



First Row: $|V_{us}|$

$$\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 I_{K\ell}(\lambda_{+,0}) (1+\delta^K_{SU(2)}+\delta^{K\ell}_{em})^2$$

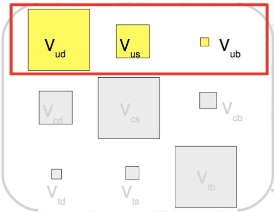
with $K = K^+, K^0; \ell = e, \mu$ and $C_K^2 = 1/2$ for K^+, 1 for K^0

Inputs from theory:

S_{EW}	Universal short distance EW correction (1.0232)
$\delta^K_{SU(2)}$	Form factor correction for strong SU(2) breaking
$\delta^{K\ell}_{em}$	Long distance EM effects
$f_+^{K^0\pi^-}(0)$	Hadronic matrix element at zero momentum transfer (t=0)

Inputs from experiment:

$\Gamma(K_{l3(\gamma)})$	**Branching ratios** with well determined treatment of radiative decays; **lifetimes**
$I_{K\ell}(\lambda)$	Phase space integral: λ's parameterize form factor dependence on t : K_{e3}: *only* λ_+ $K_{\mu 3}$: *need* λ_+ *and* λ_0



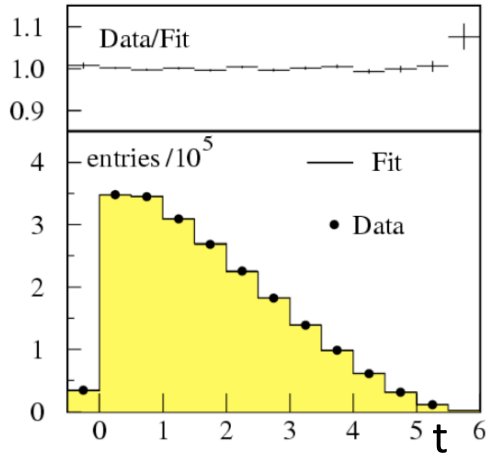
Sibidanov, CKM 2008

First Row: $|V_{us}|$

KLOE V_{us} Measurement with K_{l3}

K_{Se3}	PLB 636(2006) 173	K_S BRs
$K_S \to \pi\pi$	EPJC 48(2006) 767	
K_L decay distribution(τ)	PLB 626(2005) 15	
K_L decays and lifetime	PLB 632(2006) 43	K_L BRs
$K_L \to \pi^+\pi^-$	PLB 638(2006) 140	lifetime
$K_L \to \gamma\gamma$	PLB 566(2003) 61	FFs
K^0 mass	JHEP 12(2007) 073	
$K_{Le3\gamma}$	EPJC 55(2008) 539	
ff K_{Le3}	PLB 636(2006) 166	
ff $K_{L\mu3}$	JHEP 12(2007) 105	
$K^+_{\mu2}$	PLB 632(2006) 76	$K^\pm$ BRs
K^+ lifetime	JHEP 01(2008) 073	lifetime
K^+_{l3}	JHEP 02(2008) 098	
$K^+_{\tau'}$	PLB 597(2004) 139	
$K^+_{\pi2}$	PLB 666(2008) 305	

Form Factor Dependence Fit



$\tilde{f}_+(t)$

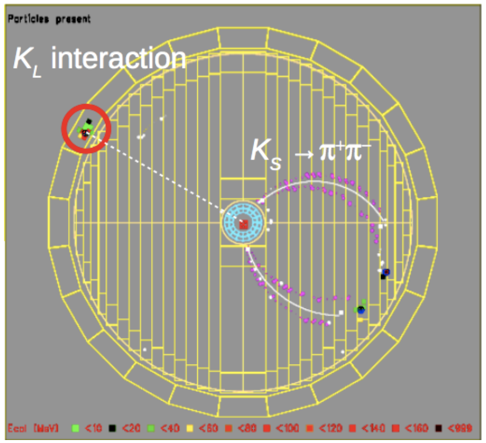
We can select high purity sample of K_{Le3} decays by kinematics and make e/μ separation by TOF

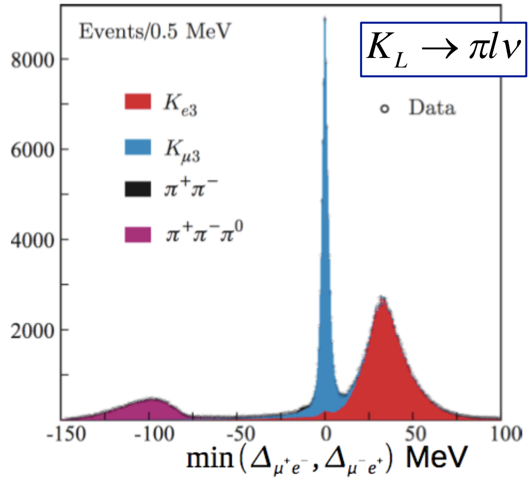
Quadratic parametrization:

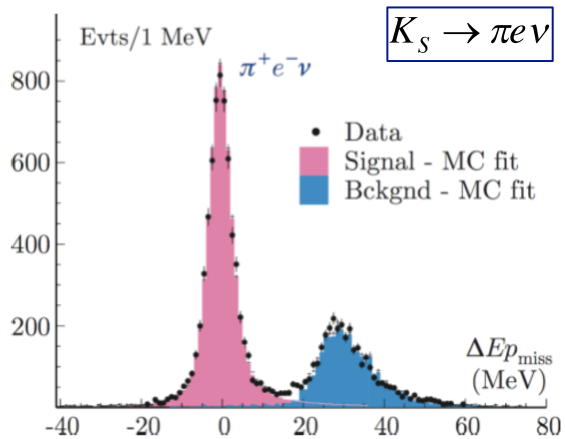
$$\lambda'_+ = (22.5 \pm 1.5_{\rm stat} \pm 1.0_{\rm syst}) \times 10^{-3}$$
$$\lambda''_+ = (1.4 \pm 0.7_{\rm stat} \pm 0.4_{\rm syst}) \times 10^{-3}$$

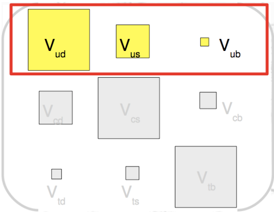
Pole parametrization:

$$M_V = 870 \pm 6_{\rm stat} \pm 7_{\rm syst}\ {\rm MeV}$$







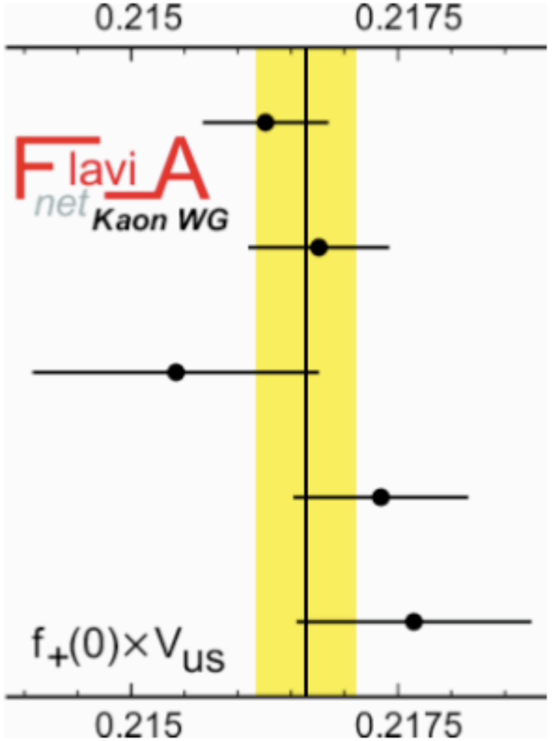


Sciascia, CKM 2008

First Row: $|V_{us}|$

KLOE Result: $|V_{us}|f_+(0) = 0.2157(6) \quad \chi^2/ndf = 7.0/4 \quad (14\%)$

JHEP 04(2008) 059



$K_L e3$	**0.2164(6)**
$K_L \mu 3$	**0.2170(6)**
$K_S e3$	**0.2156(13)**
$K^\pm e3$	**0.2174(8)**
$K^\pm \mu 3$	**0.2177(11)**

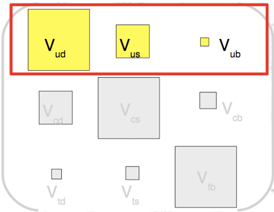
- Evaluate $V_{us} f_+(0)$ by charge:

  $K_{L,S}$ = 0.2165(5),

  $K^\pm$ = 0.2174(8)

- Average: 0.2167(5), **χ^2/ndf = 1.04/1** (31% probability).

Average: $|V_{us}|f_+(0) = 0.2167(5) \quad \chi^2/ndf = 2.83/4 \quad (59\%)$



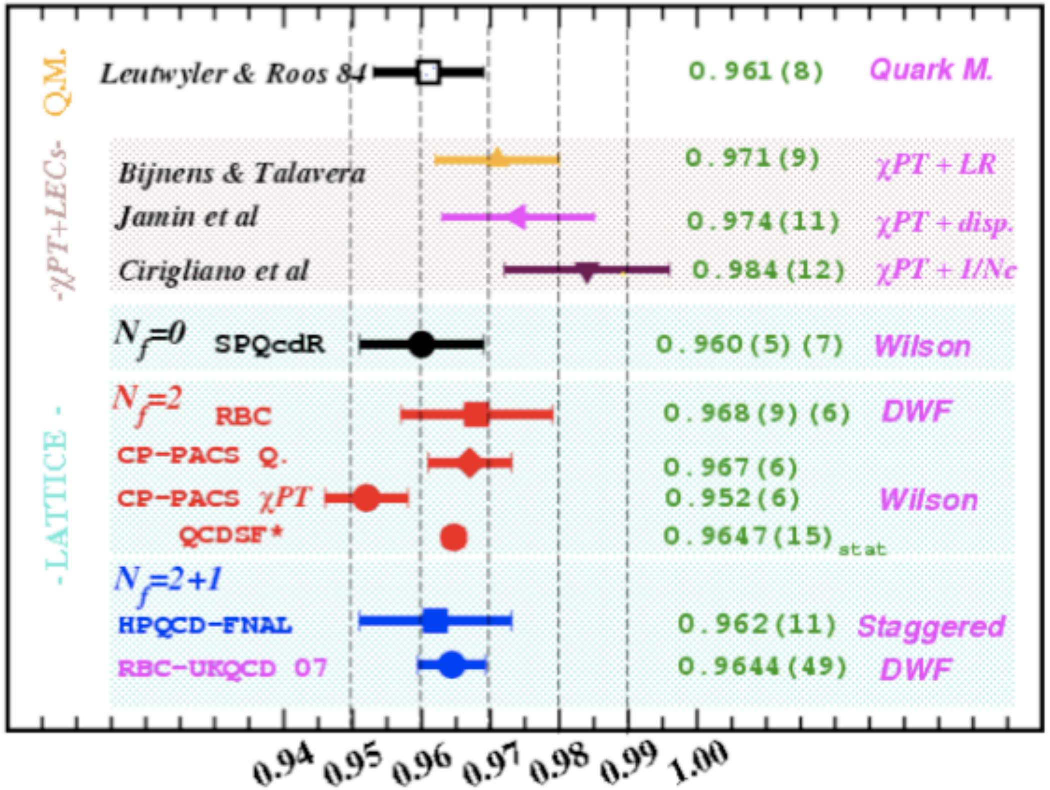
First Row: $|V_{us}|$

Theoretical Estimates of $f_+(0)$

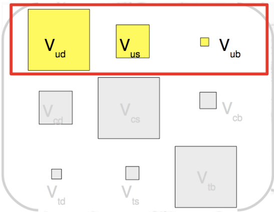
Sciascia, CKM 2008

Leutwyler & Roos estimate still widely used: $f_+(0) = 0.961(8)$.

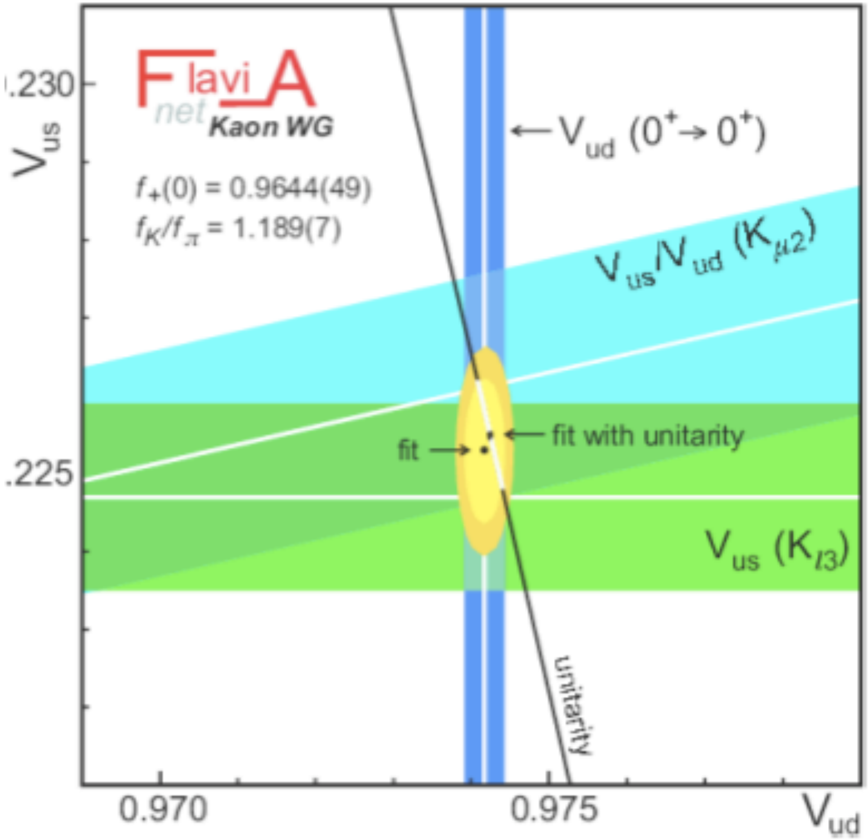
Lattice evaluations generally agree well with this value; use RBC-UKQCD07 value: $f_+(0) = 0.9644(49)$ (0.5% accuracy, also syst. err.).



$$V_{us} = 0.2247 \pm 0.0012$$



Sciascia, CKM 2008



First Row: $|V_{us}|$

Unitarity Test

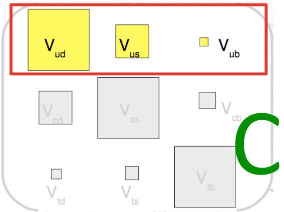
$V_{us} = 0.2247 \pm 0.0012$

$V_{us}/V_{ud} = 0.2322 \pm 0.0015$

$V_{ud} = 0.97425 \pm 0.00023$

$$1 - |V_{ud}|^2 - |V_{us}|^2 = 0.00003 \pm 0.00060$$

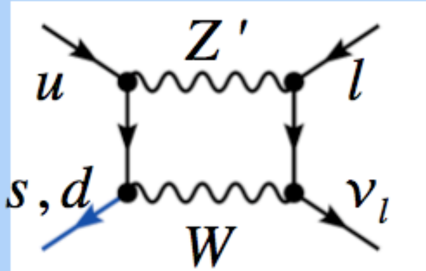
Was 0.0031 ± 0.0015 in PDG04



Constraints on NP from 1st Row Unitarity

$G_F = 1.166371(6)\times10^{-5}$ GeV^{-2}

$G_{CKM} = 1.16614(40)\times10^{-5}$ GeV^{-2}



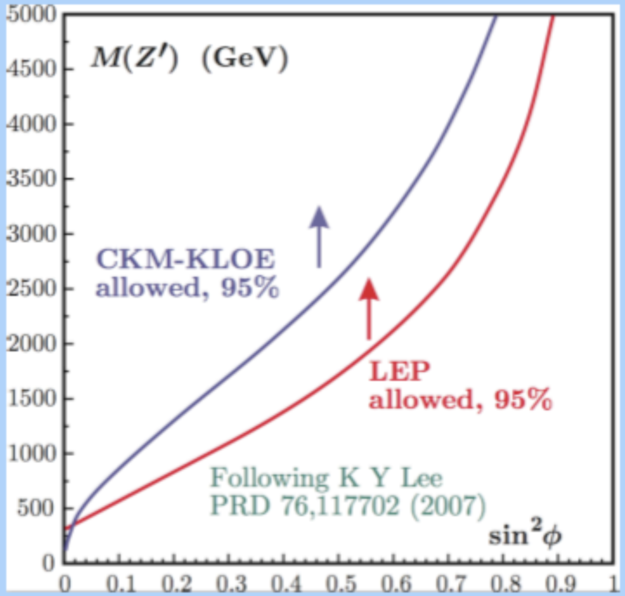
$$G_F = G_{CKM}\left(1 - 0.007 Q_{eL}(Q_{\mu L} - Q_{dL})\frac{2\ln\frac{m_{Z'}}{m_W}}{\frac{m_{Z'}^2}{m_W^2} - 1}\right)$$

SO(10) Z_χ boson:

$m_{Z\chi}$ > 750 GeV 95% CL

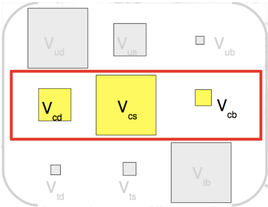
[Marciano]

Tree level breaking of unitarity in model with non-universal gauge interaction



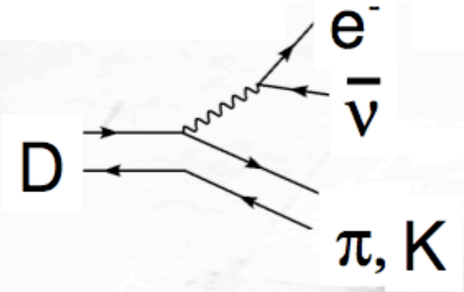
The "power of flavour "!

KLOE: Sibidanov, CKM 2008



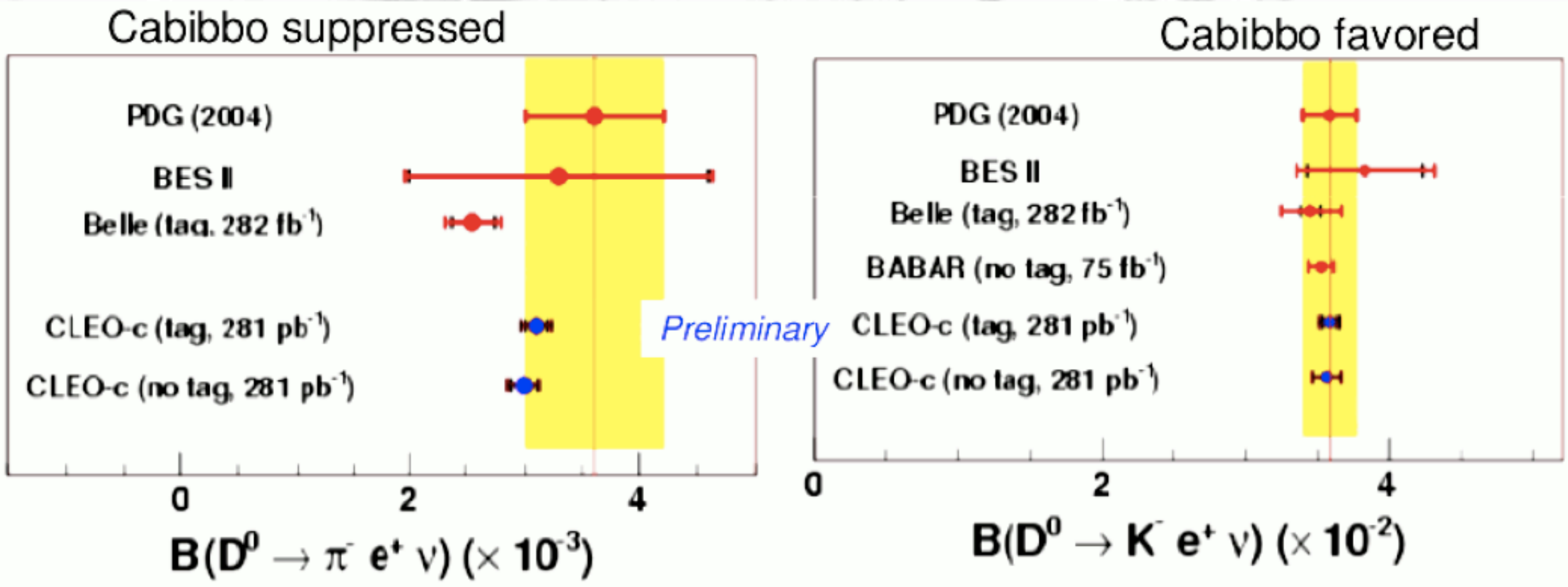
Di Lodovico, ICHEP 2008

Second Row: $|V_{cd}|$, $|V_{cs}|$

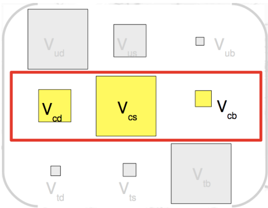


$$\frac{d\Gamma(D^+\to\pi(K)e\nu)}{dq^2} = \frac{G_F^2}{24\pi^3} P_{\pi(K)}^3 |V_{cd(s)}|^2 |f_+(q^2)|^2$$

Theory input

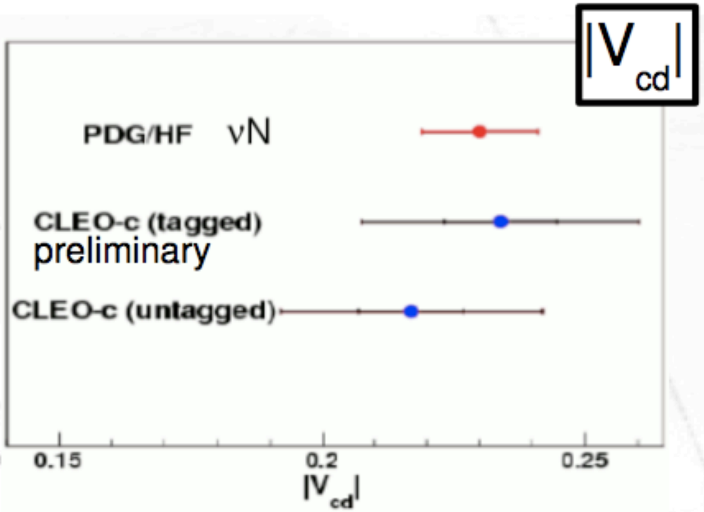


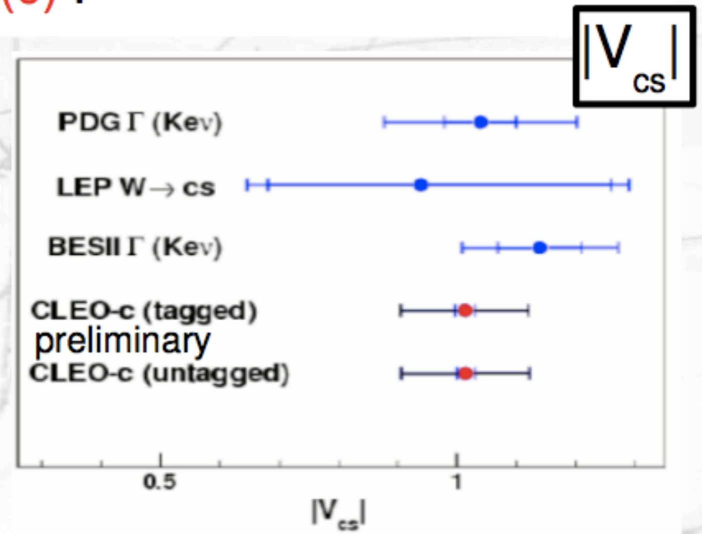
Significantly improved precision due to the BaBar, Belle and CLEO-c results



Second Row: $|V_{cd}|$, $|V_{cs}|$

Using Becher-Hill form factor parametrization (Phys. Lett. B633 61 (2006)) with FNAL-MILC-HPQCD calculations for $f_+(0)$:





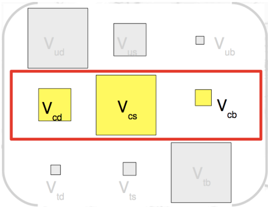
Most precise determination from νN interactions:

$|V_{cd}| = 0.230 \pm 0.011$

Most precise determination from CLEO-c tagged measurement:

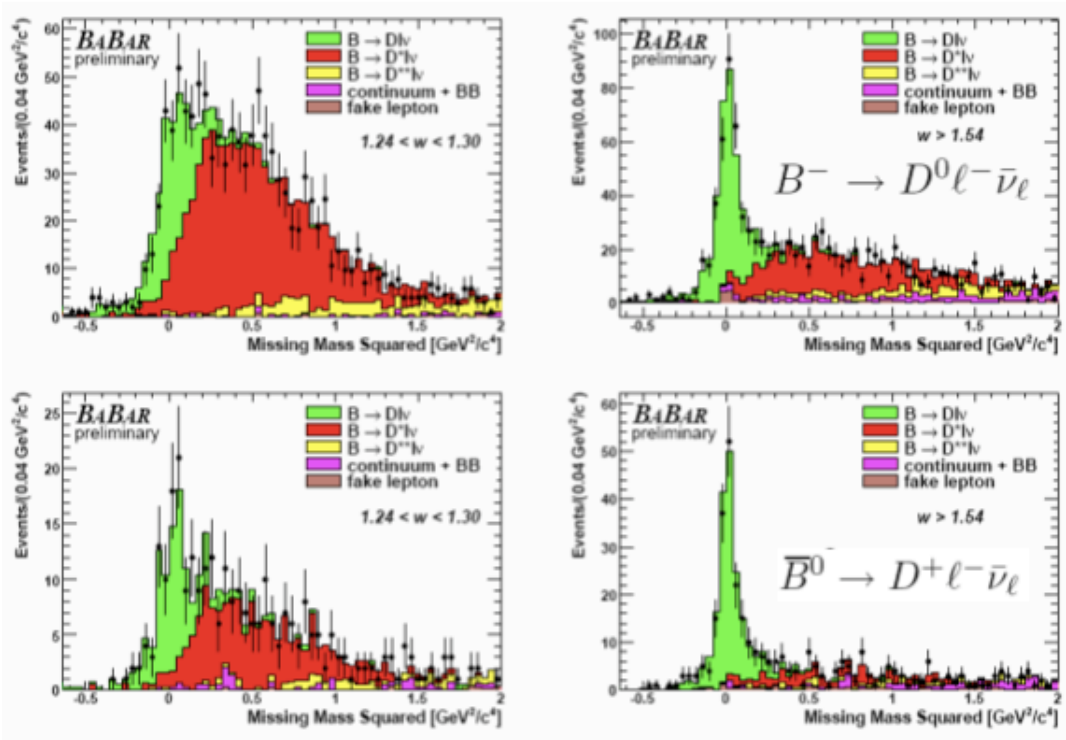
$|V_{cs}| = 1.014 \pm 0.013_{stat} \pm 0.009_{syst} \pm 0.106_{LQCD}$

Di Lodovico, ICHEP 2008



Second Row: $|V_{cb}|$

$$\frac{d\Gamma(\bar{B}\to Dl^-\bar{\nu})}{d\omega\, d\cos\theta_l\, d\cos\theta_V\, d\chi} \propto G^2(\omega)\,|V_{cb}|^2$$



- ω is related to q^2 of the B meson to the D

BABAR, preliminary ICHEP 2008

Global fit to $D\ell\nu$ and $D^*\ell\nu$

$\rho^2_D = 1.23 \pm 0.04 \pm 0.07$

$\rho^2_{D^*} = 1.21 \pm 0.02 \pm 0.07$

$G(1)\,|V_{cb}| = (44.1 \pm 0.8 \pm 2.2) \times 10^{-3}$

$F(1)|V_{cb}| = (35.6 \pm 0.2 \pm 1.2) \times 10^{-3}$

$B \to D\ell\nu$

$\rho^2_D = 1.20 \pm 0.09 \pm 0.04$

$G(1)\,|V_{cb}| = (43.0 \pm 1.9 \pm 1.4) \times 10^{-3}$

BELLE, preliminary ICHEP 2008

$B \to D^*\ell\nu$

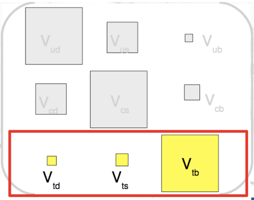
$\rho^2_{D^*} = 1.293 \pm 0.045 \pm 0.029$

$R_1 = 1.495 \pm 0.050 \pm 0.062$

$R_2 = 0.844 \pm 0.034 \pm 0.019$

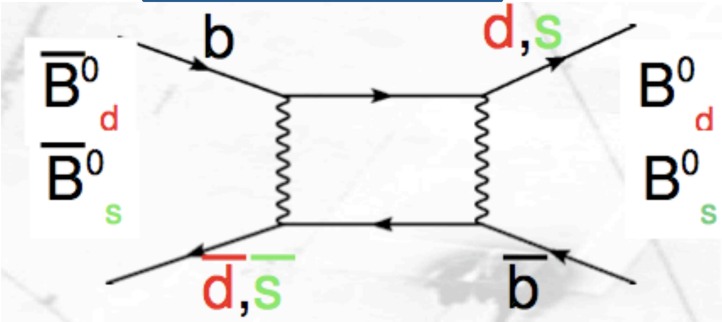
$F(1)|V_{cb}| = (34.4 \pm 0.2 \pm 1.0) \times 10^{-3}$

Di Lodovico, ICHEP 2008



Third Row: $|V_{td}|$, $|V_{ts}|$

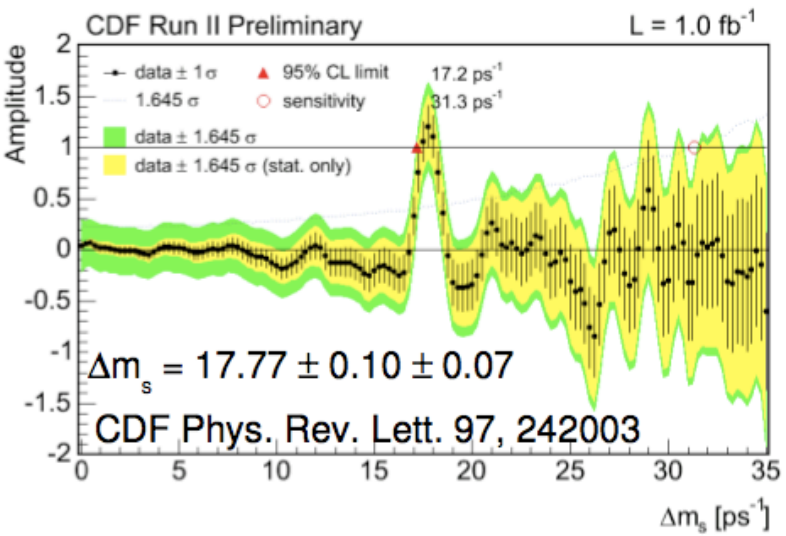
Di Lodovico, ICHEP 2008

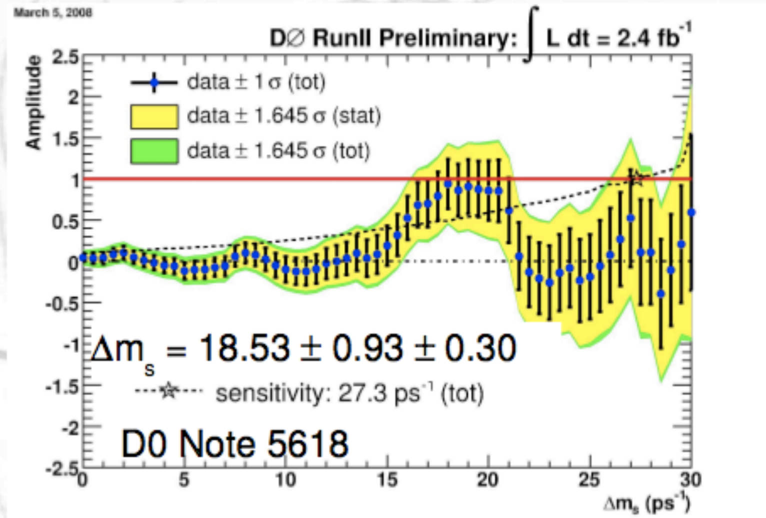


Slow oscillation
Fast oscillation

$$\frac{\Delta m^2_s}{\Delta m^2_d} = \frac{m_{Bs} f^2_{Bs} B_{Bs} |V_{ts}|^2}{m_{Bd} f^2_{Bd} B_{Bd} |V_{td}|^2}$$

Theoretical uncertainties reduced in the ratio





$|V_{td}|/|V_{ts}| = 0.207 \pm 0.001_{exp} \pm 0.006_{theo}$

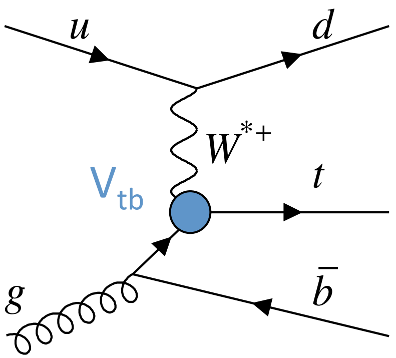
for $(f_{Bs}\sqrt{B_{Bs}}) / (f_{Bd}\sqrt{B_{Bd}}) = 1.21 \pm 0.04$

arXiv:0807.4605 [hep-ph]
and references therein

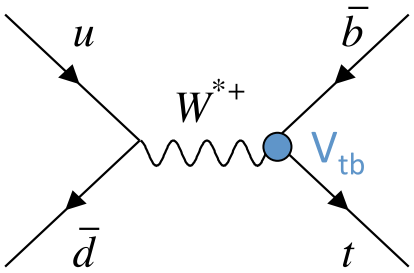
Junk, ICHEP 2008

Third Row: $|V_{tb}|$

- Single top production cross section proportional to $|V_{tb}|^2$

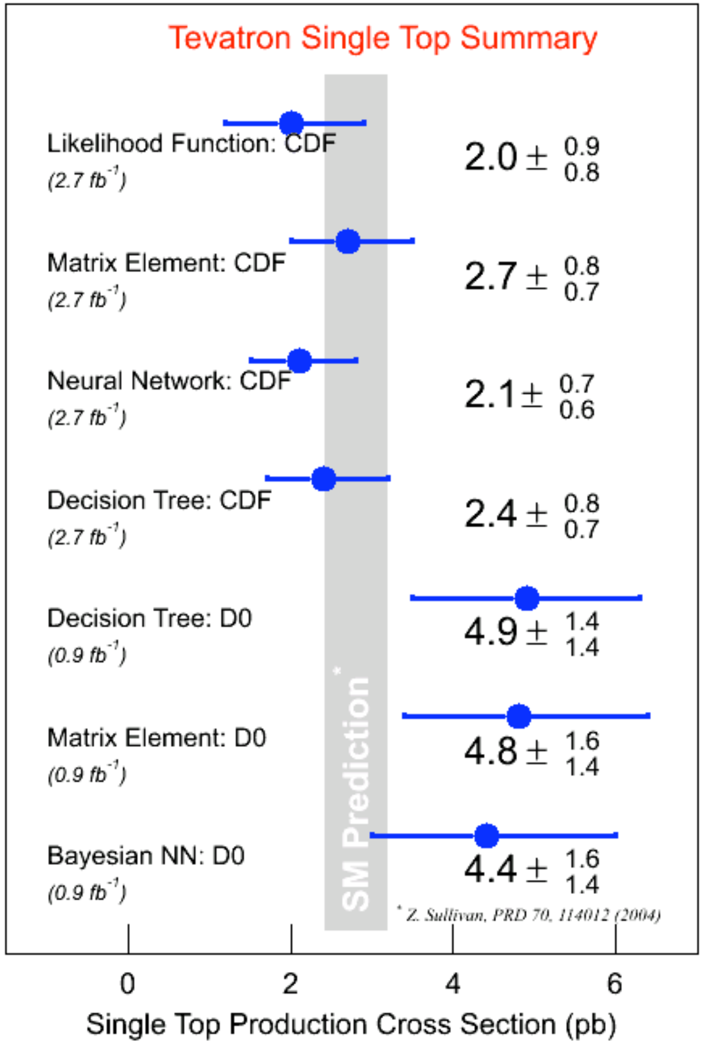


t-channel production



s-channel production

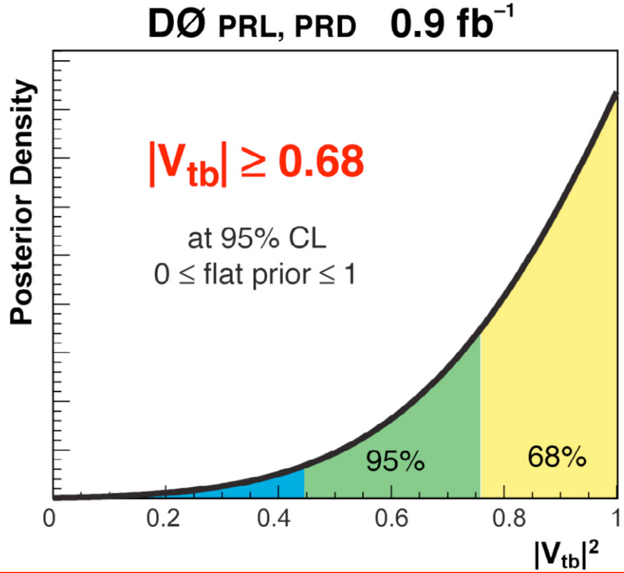
- Recent new results from CDF and D0 of single top production at Tevatron
  - – first evidence at ~3.7σ !

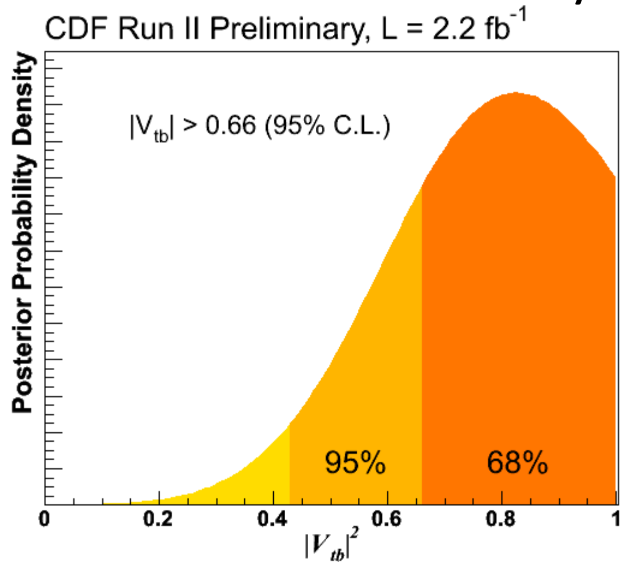


Li, ICHEP 2008

Third Row: $|V_{tb}|$

- Direct measurement of $|V_{tb}|$ from cross section measurement:
  - $\sigma \propto |V_{tb}|^2$
- Assuming standard model production:
  - Pure V-A and CP conserving Wtb interaction
  - $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$
  - Additional theoretical errors enter (top mass, scale, PDF etc…)
- No need to assume three quark generations or CKM unitarity

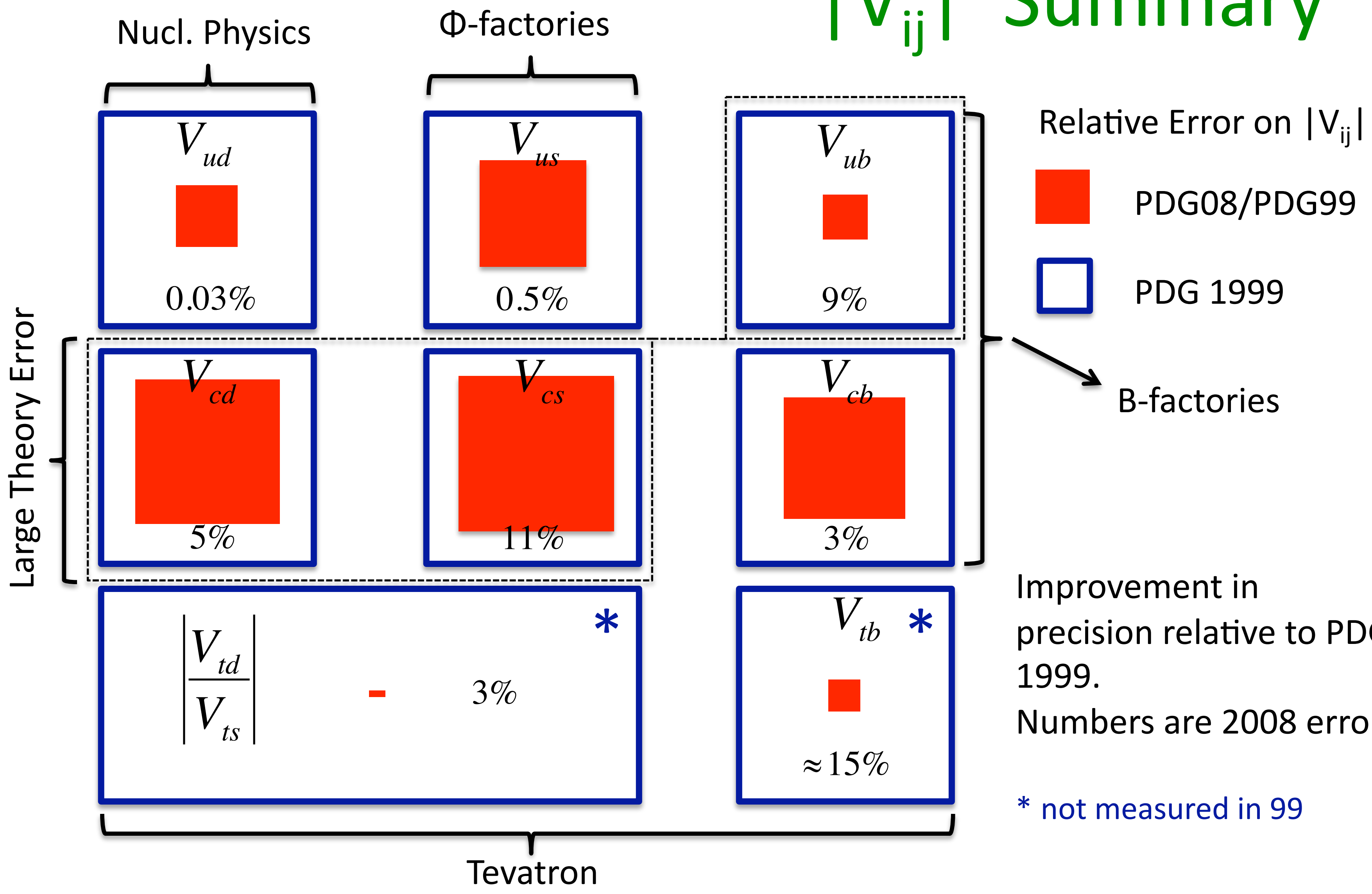




$$|V_{tb}| = 1.00^{+0.00}_{-0.12}\ (\exp + th.)$$

$$|V_{tb}| = 0.88 \pm 0.14\,(\exp) \pm 0.07\,(th.)$$

|V_{ij}| Summary

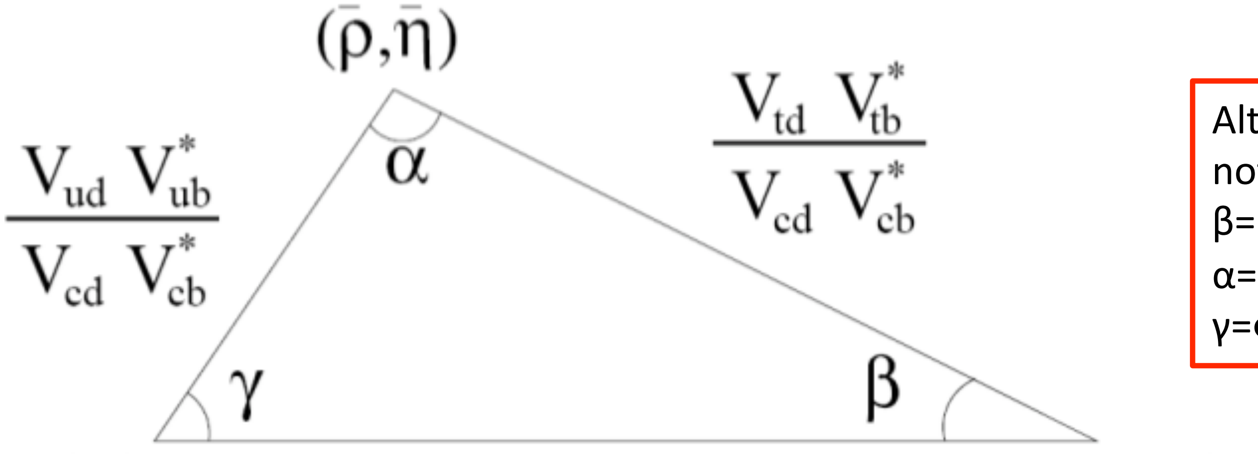


Improvement in precision relative to PDG 1999.
Numbers are 2008 errors

* not measured in 99

Angles of Unitarity Triangle

B-factories



(0,0) $\bar{\rho} \approx \rho(1-\lambda^2/2), \quad \bar{\eta} \approx \eta(1-\lambda^2/2)$ (1,0)

Alternative notation:
$\beta = \phi_1$
$\alpha = \phi_2$
$\gamma = \phi_3$

B^0

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$ interference between b→u & mixing

$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$ interference between b→c & mixing

$A_{CP}(\Delta t)$ → Asymmetric Beams

$B^{0,\pm}$

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$ interference between b→u & b→c

Time Dependent CP Asymmetry

- The time evolution of a flavour tagged (B^0 or $\bar{B}^0$) physical state B_{TAG} decaying to a final state f with CP eigenvalue $\eta_f=\pm1$ is

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left\{1 \pm \left[-\eta_f S \sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)\right]\right\}$$

where:

$$S = \frac{2\cdot\Im\lambda_f}{1+|\lambda_f|^2}$$

$$C = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

CPV parameter: $\lambda = \frac{q}{p}\frac{\bar{A}_f}{A_f} = \left|\frac{q}{p}\right| \cdot \left|\frac{\bar{A}_f}{A_f}\right| \cdot e^{i(\phi_m+\delta)}$

$$\Im\lambda = \sin(\phi_m + \delta)$$

mixing phase (ϕ_m)

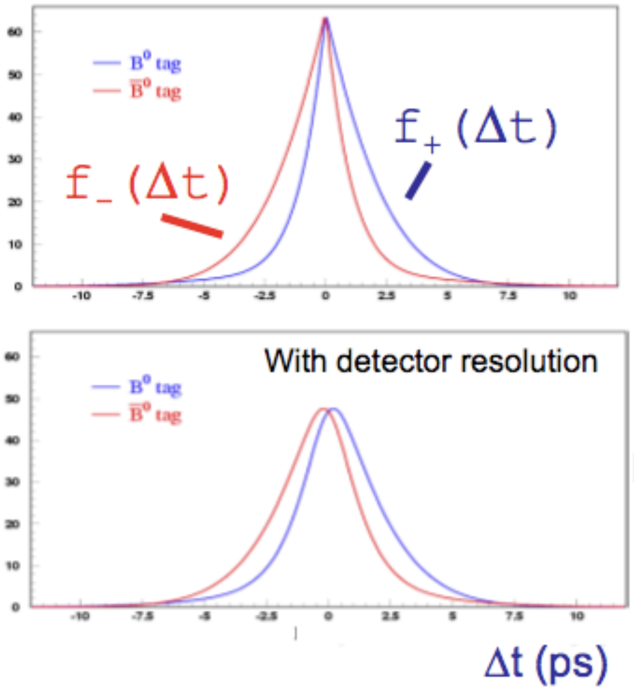
strong phase difference between A_f and $\bar{A}_f$ (δ)

$$CPV \Rightarrow \lambda \neq 1 \quad possible\, even\, if \left|\frac{q}{p}\right| = 1\ and \left|\frac{\bar{A}_f}{A_f}\right| = 1$$

Time Dependent CP Asymmetry

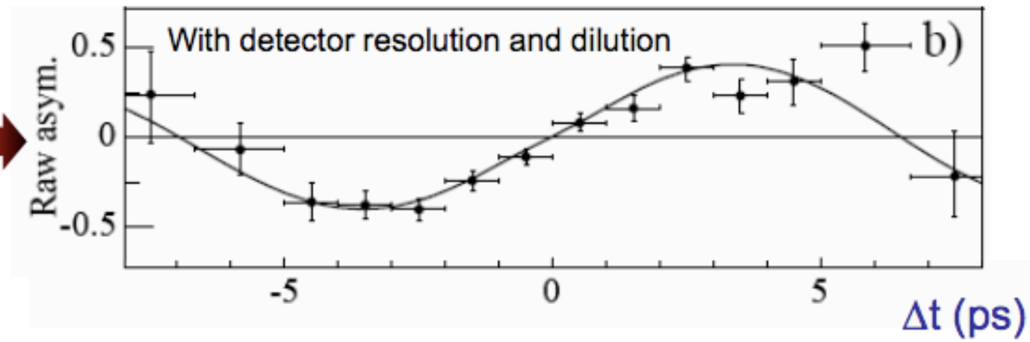
One can construct an asymmetry as a function of Δt:

$$A(\Delta t) = \frac{f_{+}(\Delta t) - f_{-}(\Delta t)}{f_{+}(\Delta t) + f_{-}(\Delta t)} = S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)$$



Experimental effects we need to include:

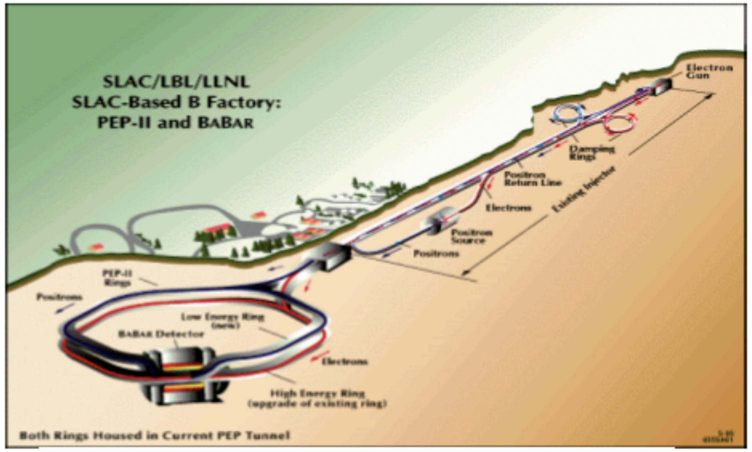
- Detector resolution on Δt.
- Dilution from flavor tagging (see later).



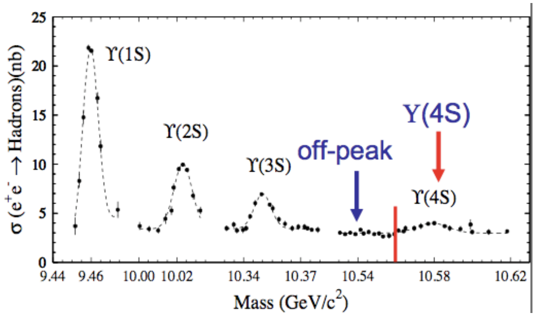
B-Factories

Asymmetric e+e- Storage Rings

PEP-II
- 9GeV e- on 3.1GeV e+
- Υ(4S) boost: βγ=0.56

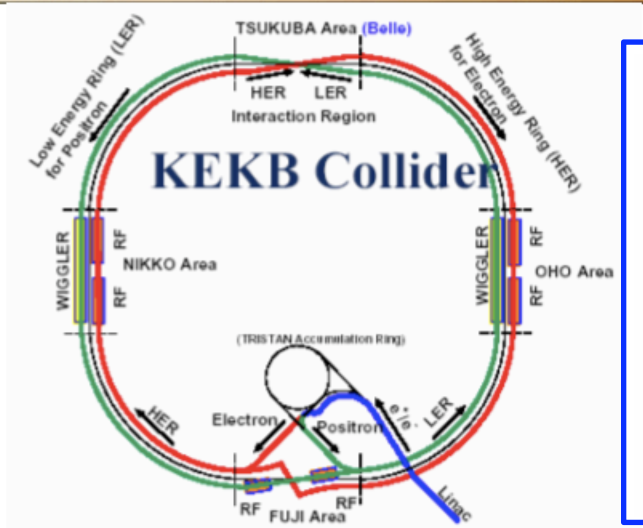


$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$$



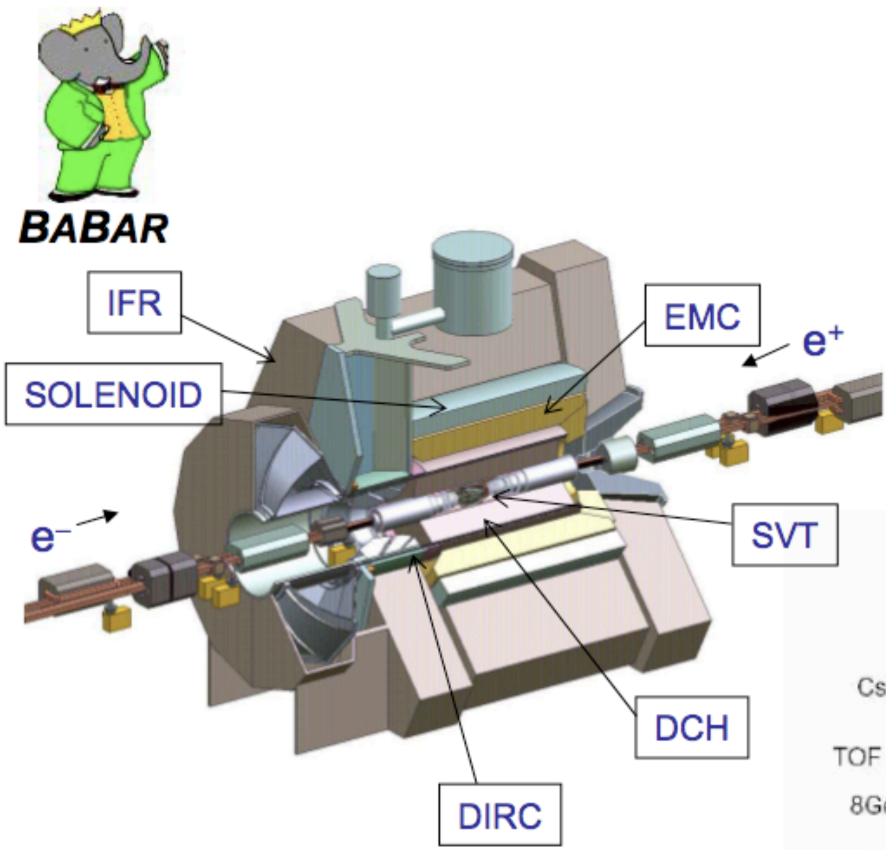
√s = 10.58 GeV/c²

KEKB
- 8GeV e- on 3.5GeV e+
- Υ(4S) boost: βγ=0.425



$e^+e^- \rightarrow$	Cross-section (nb)
$b\bar{b}$	1.05
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$d\bar{d}$	0.35
$u\bar{u}$	1.39
$\tau^+\tau^-$	0.92
$\mu^+\mu^-$	1.16
e^+e^-	~ 40

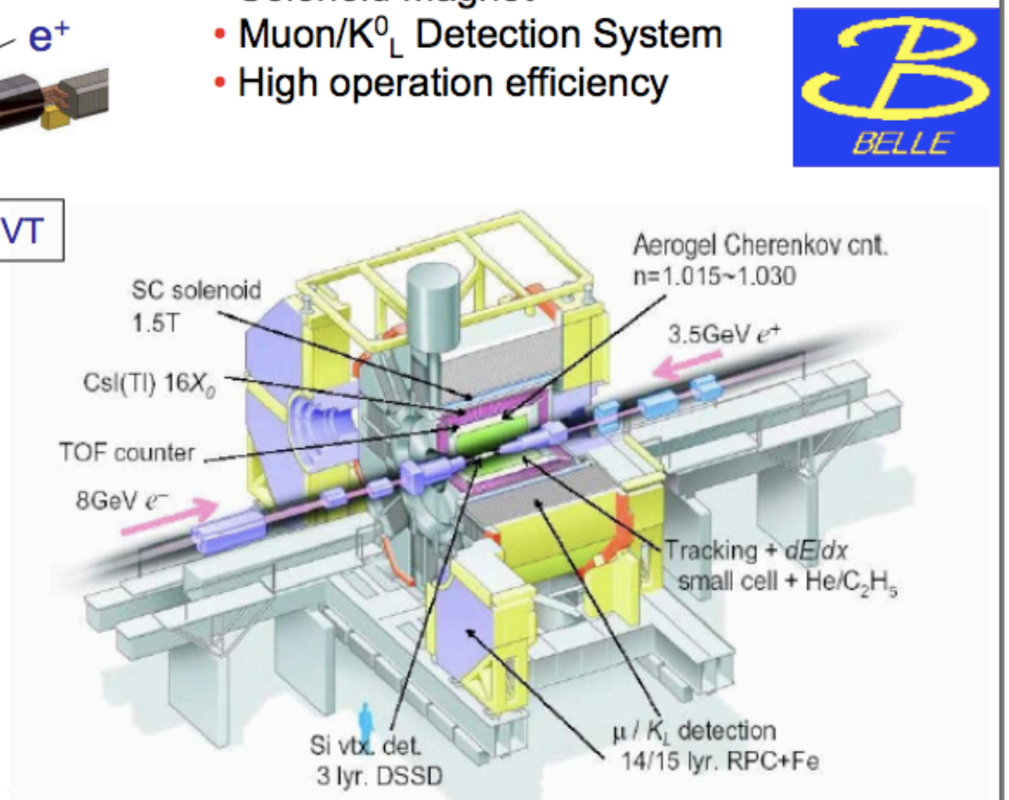
B-Factories Detectors



August 2008

The differences between the two detectors are small. Both have:

- Asymmetric design.
- Central tracking system
- Particle Identification System
- Electromagnetic Calorimeter
- Solenoid Magnet
- Muon/K^0_L Detection System
- High operation efficiency



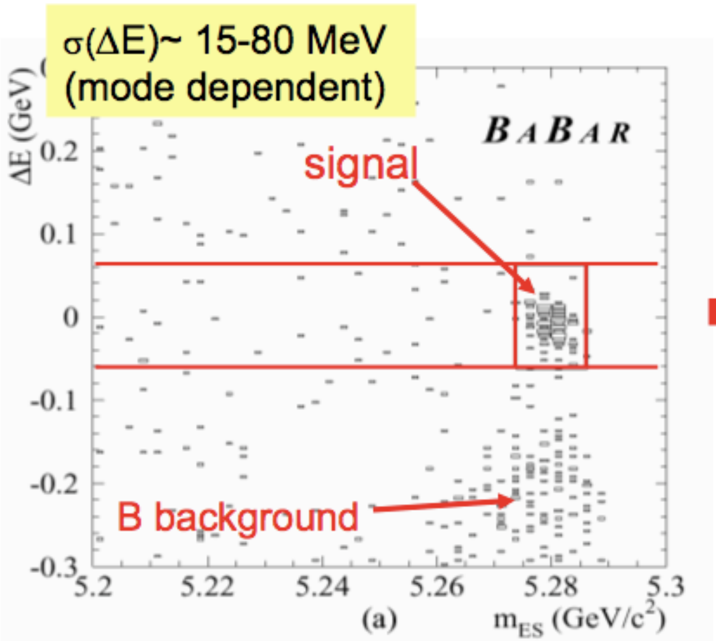
Signal Selection

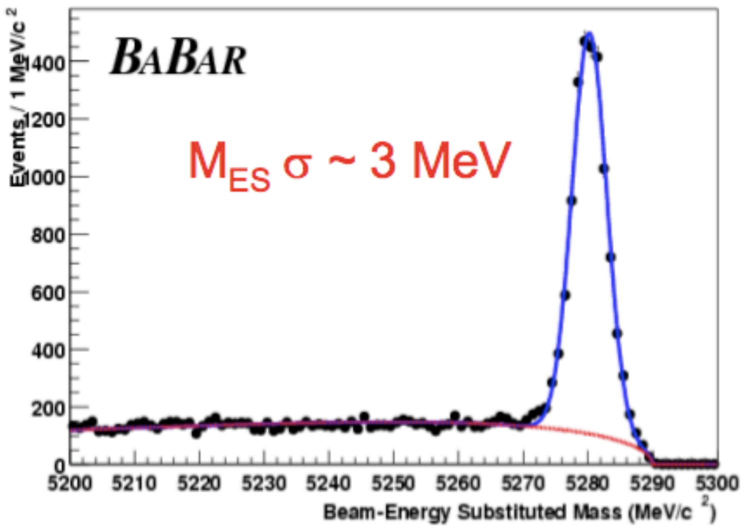
Beam energy is known very well at an e^+e^- collider

- use an energy difference and effective mass to select events:

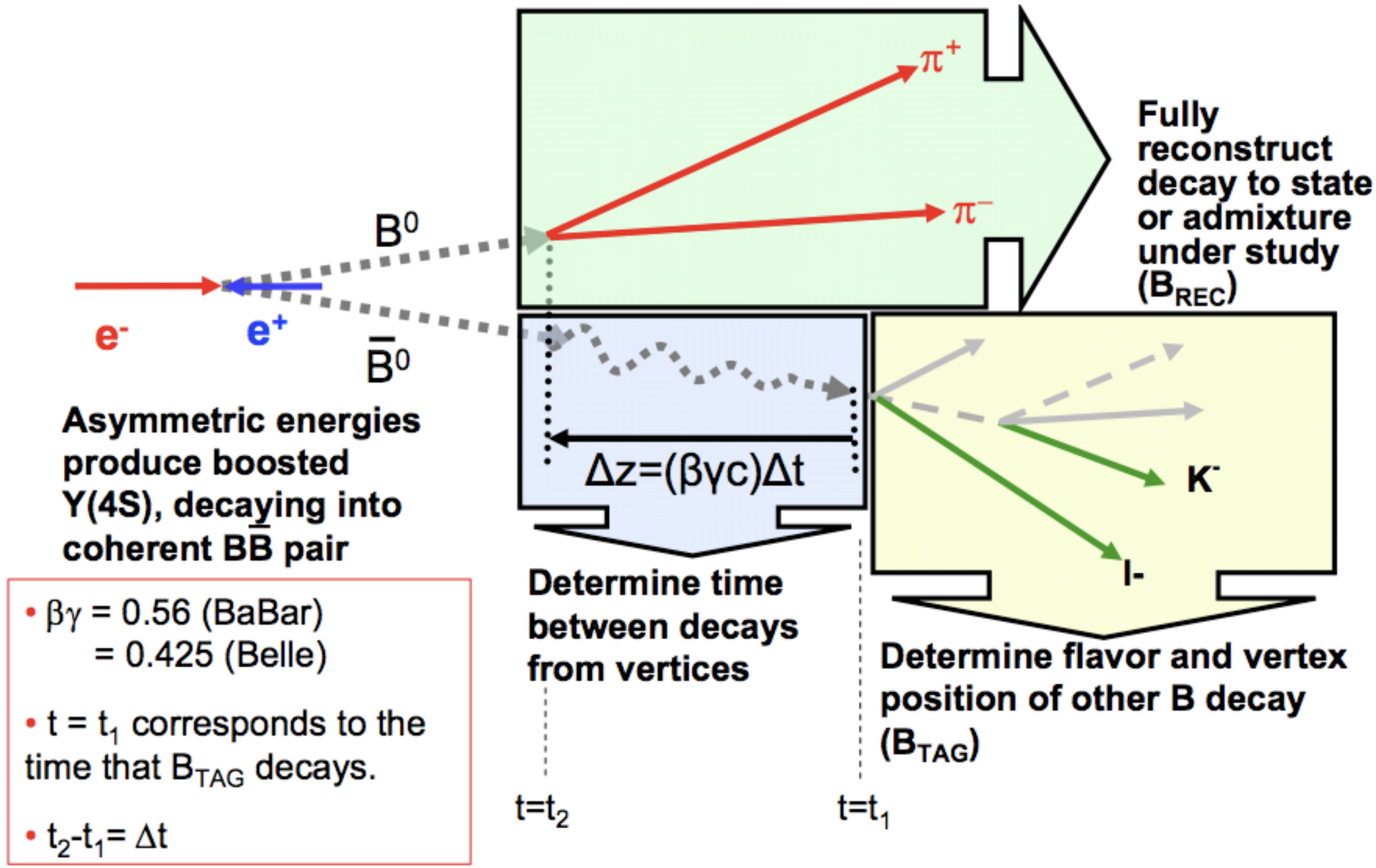
$$\Delta E = E_B^* - \sqrt{s}/2, \qquad m_{ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2},$$

- $\sqrt{s}$: beam energy in the CM frame.
- E_B^*: energy of $B_{\rm rec}$ in the CM frame.
- $\mathbf{p}_B$: momentum of $B_{\rm rec}$ in the lab frame.
- $(E_i, \mathbf{p}_i)$: four-momentum of the initial state in the lab frame.



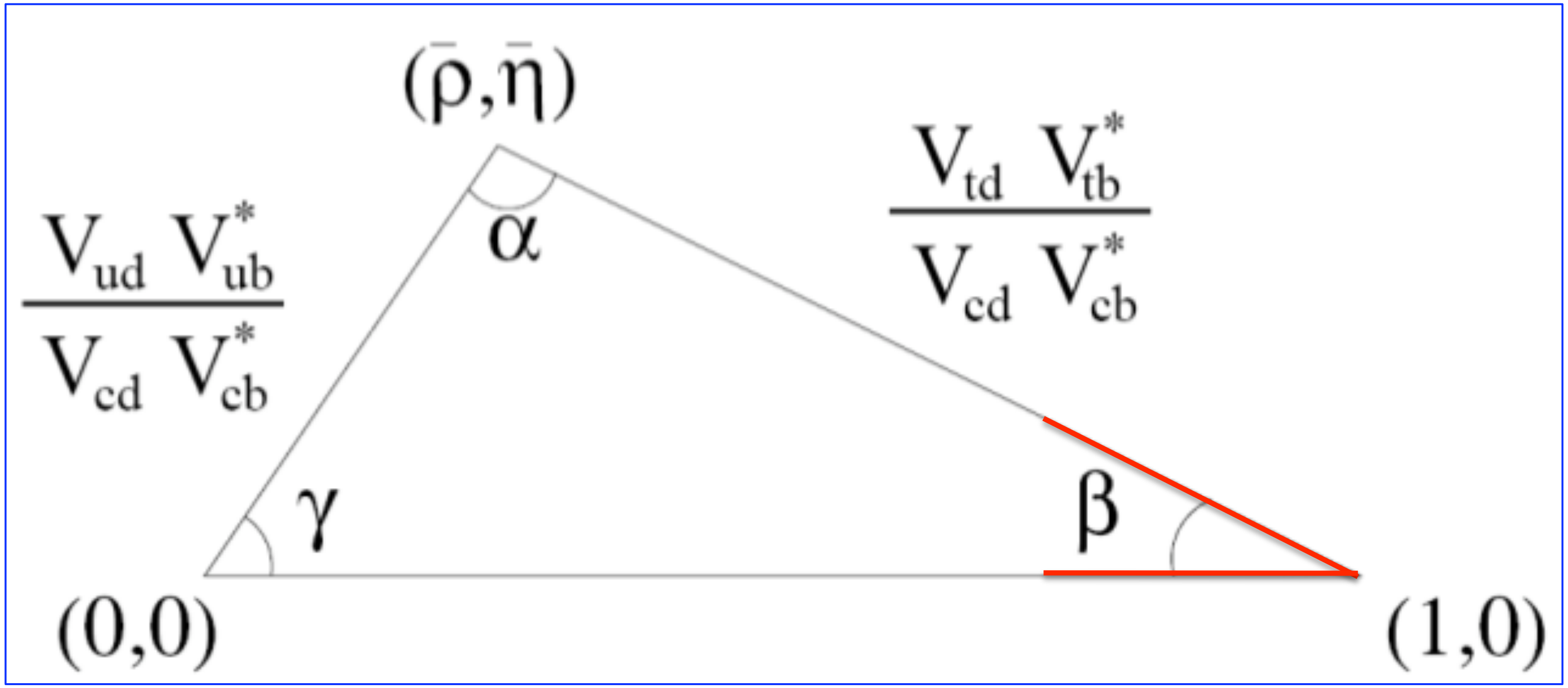


Time Measurement

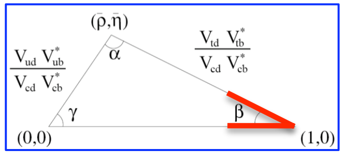


- Then fit the Δt distribution to determine the amplitude of sine and cosine terms.

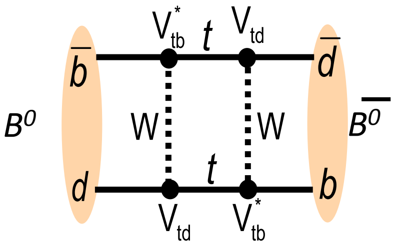
Angle β

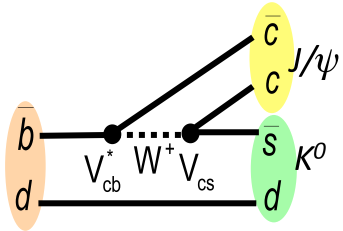


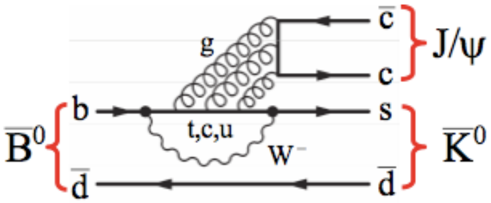
$(\bar{\rho},\bar{\eta})$
$\frac{V_{ud}\,V_{ub}^*}{V_{cd}\,V_{cb}^*}$
$\frac{V_{td}\,V_{tb}^*}{V_{cd}\,V_{cb}^*}$
α
γ
β
(0,0)
(1,0)



Angle β from "golden channel" $b \rightarrow c\bar{c}s$

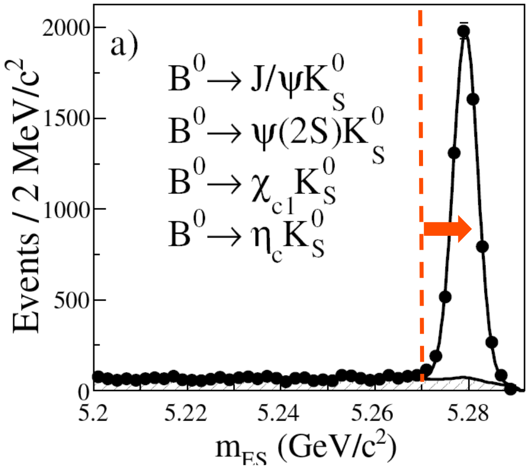




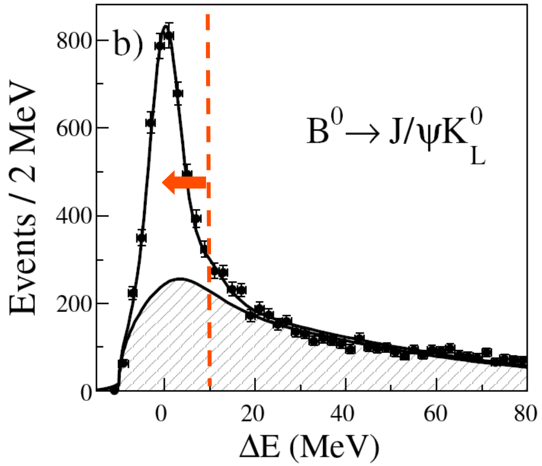


- Theoretically clean as only the tree level process dominates the decay
  - Gluonic penguin is small and has the same phase as the tree (δ=0), which gives S=sin(2β), C=0
- Measure $\sin 2\beta$ and $|\lambda|$ in several different modes

($c\bar{c}$) K^0_S (*CP* odd modes)

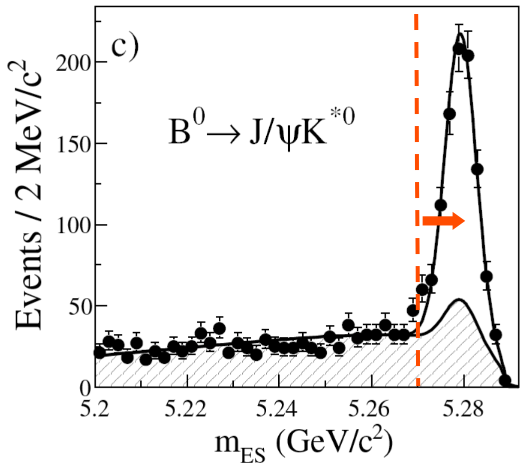


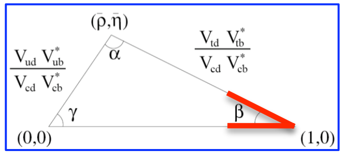
($c\bar{c}$) K^0_L (*CP* even mode)



CP admixture

BaBar



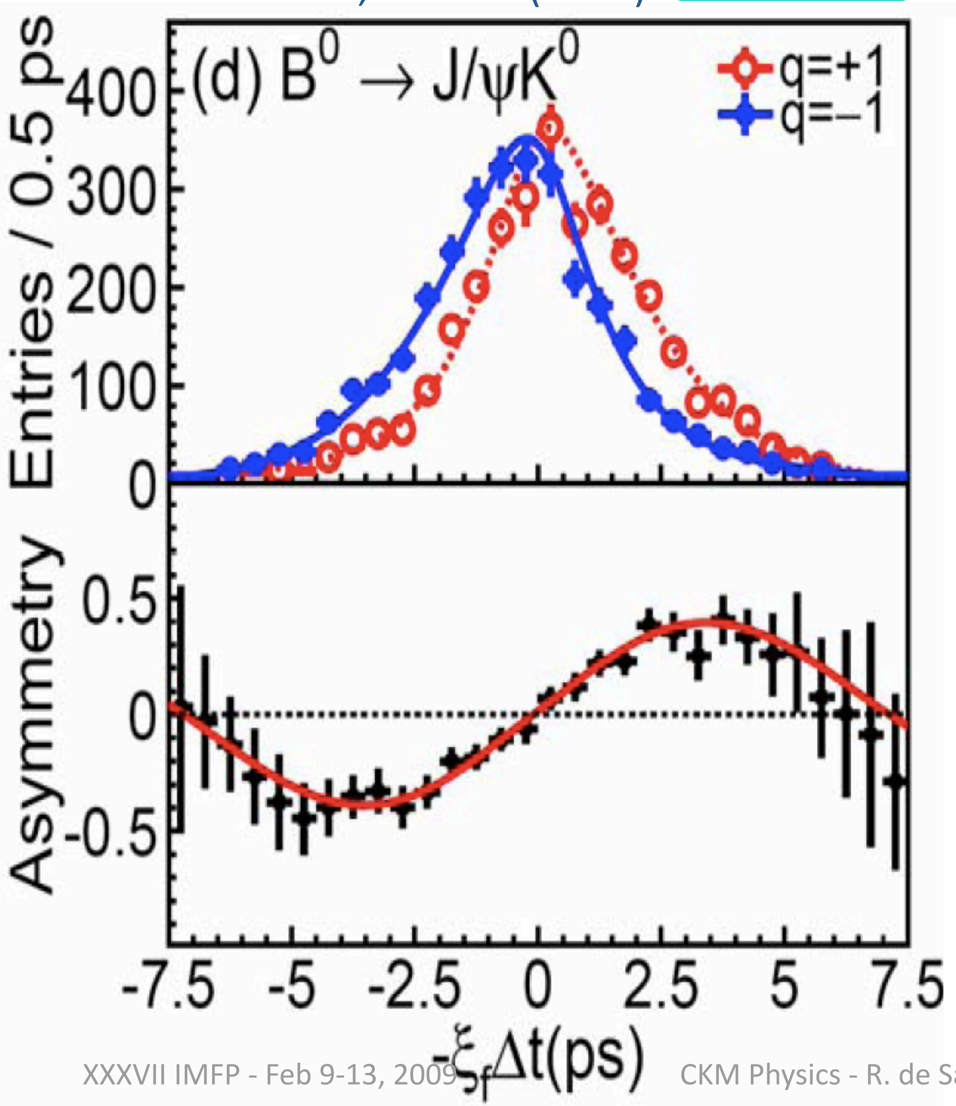


Angle β from "golden channel" $b \rightarrow c\bar{c}s$

Kolomensky, ICHEP 2008

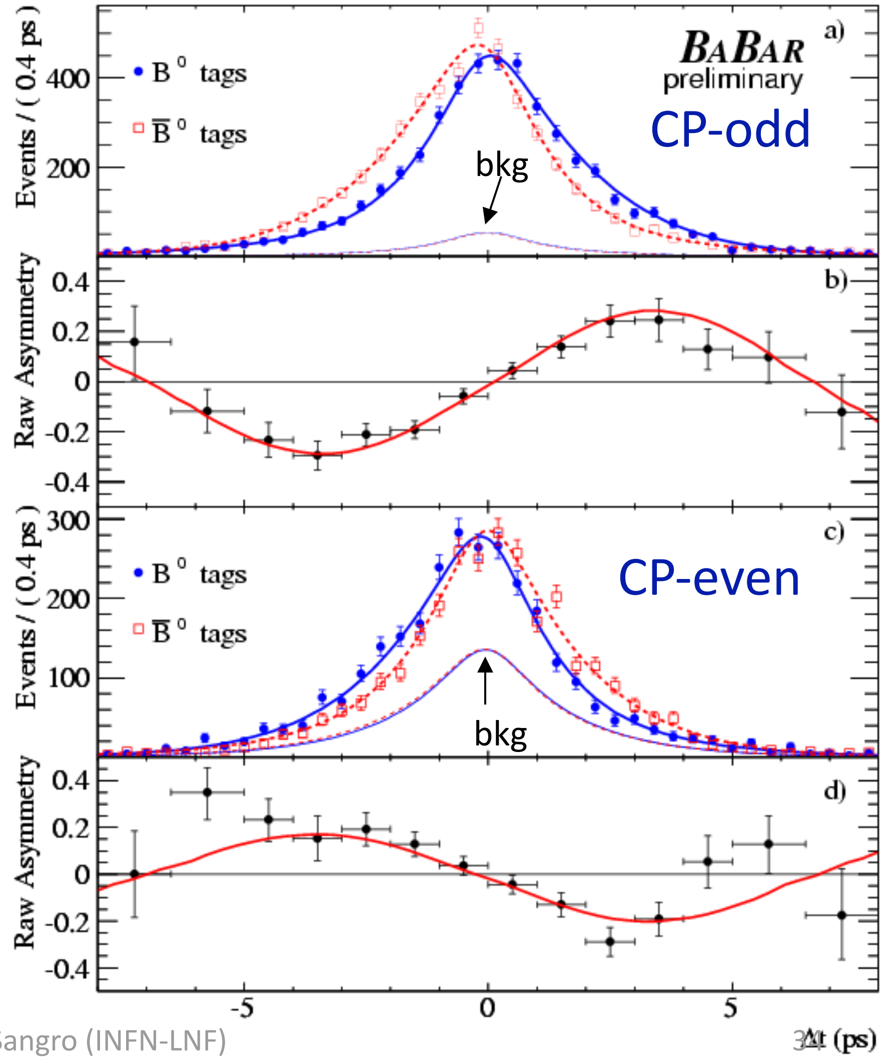
Belle: PRL**98**, 031802 (2007)

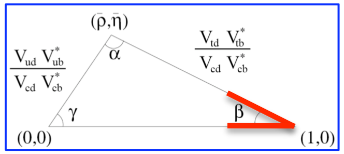
K. Vervink



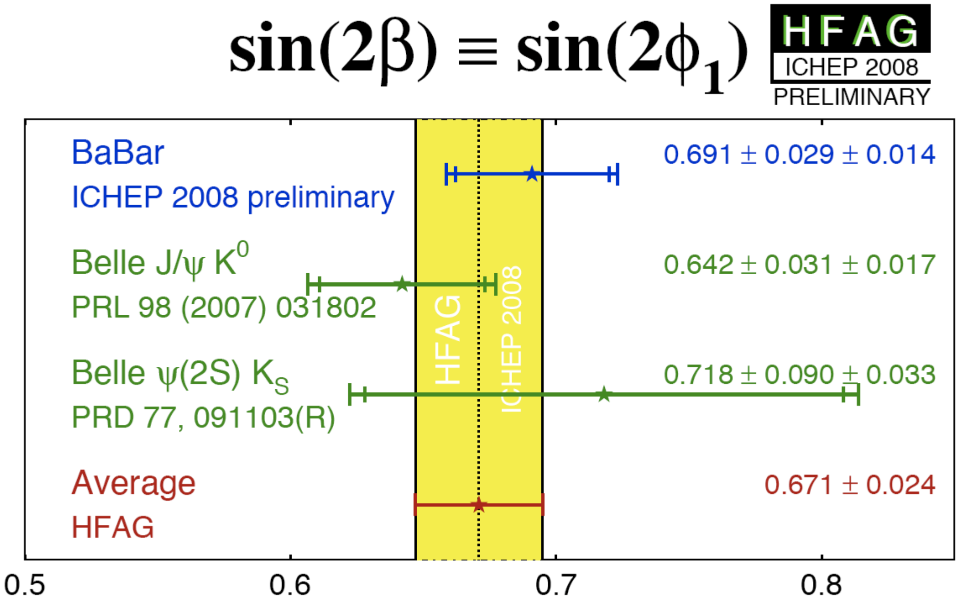
C. Chen

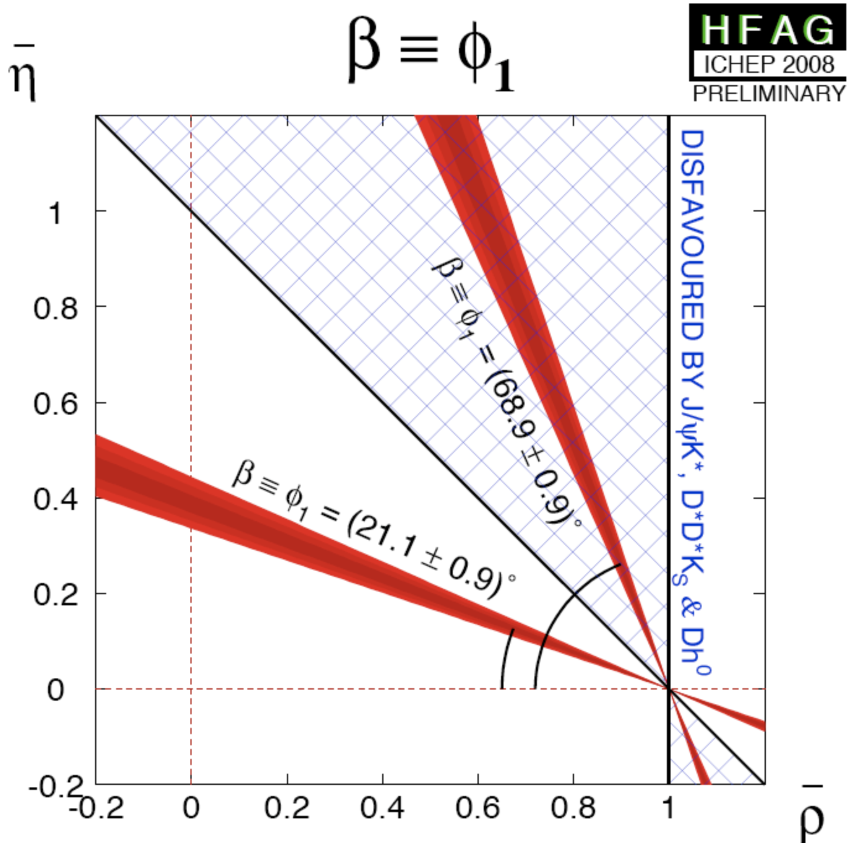
New @ ICHEP: BABAR-CONF-08/17



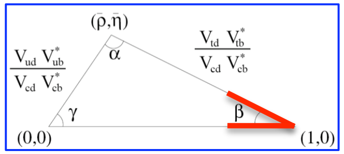


Angle β from "golden channel" $b \rightarrow c\bar{c}s$

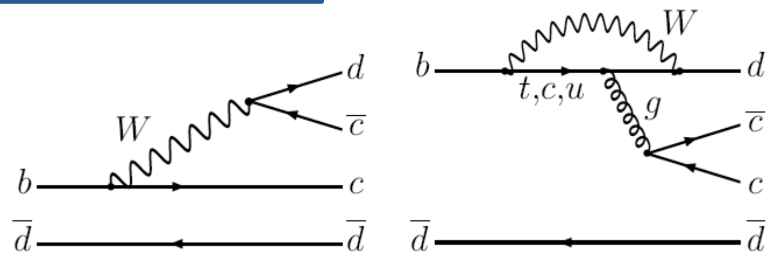




- Most precise measurements of CPV in B decays
- BaBar results is obtained with the final dataset
- Measurements are statistically limited
- Theoretical uncertainty <0.01 for sin2β from charmonium modes
- Expect further improvements from LHCb and Super B factories



Kolomensky, ICHEP 2008



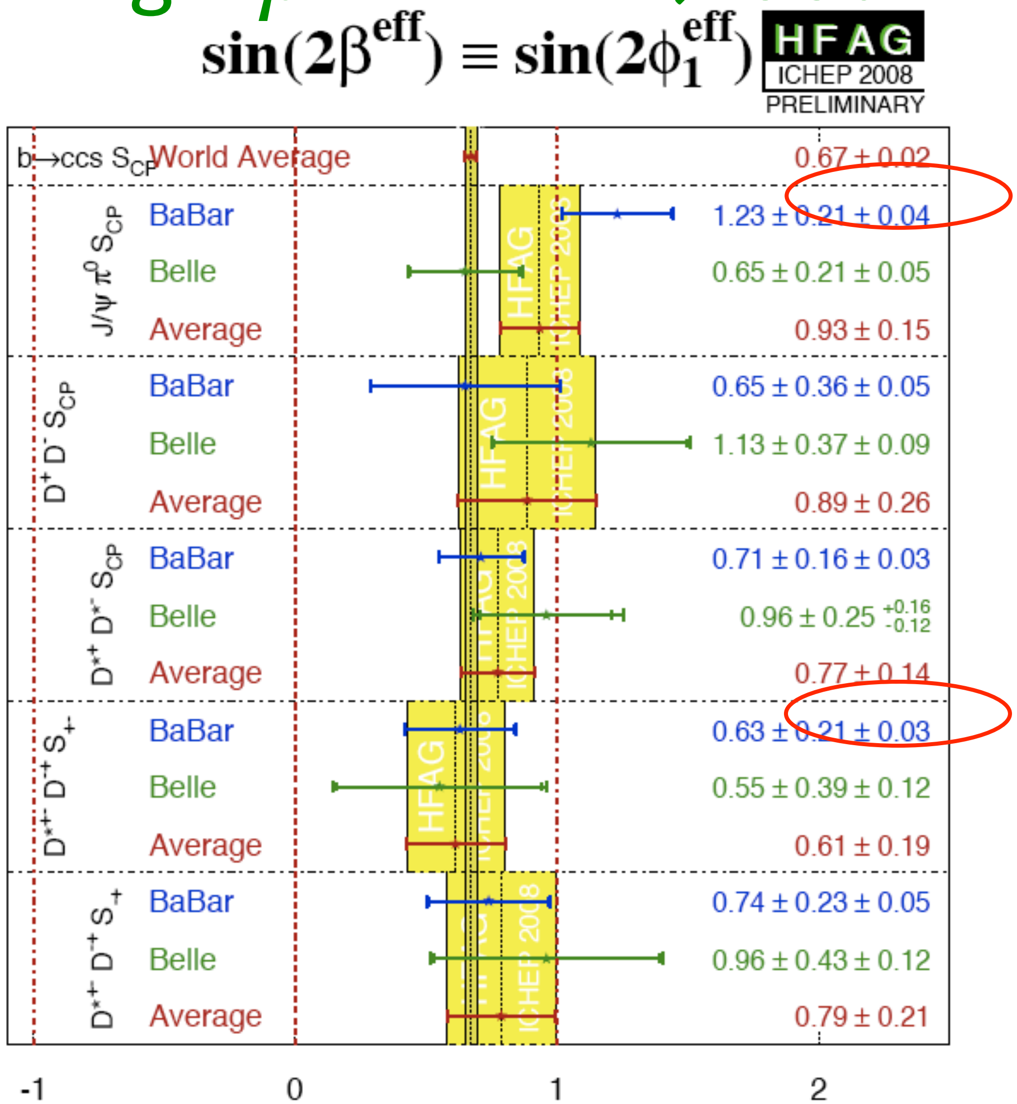
Angle β from $b \to c\bar{c}d$

Tree amplitudes Cabibbo-suppressed: potential sensitivity to penguin (loop) effects

New BaBar results this year:
$B^0 \to D^{(*)+}D^{(*)-}$: BABAR-PUB-08/39
$B^0 \to J/\Psi\,\pi^0$: PRL **101**, 021801(2008)

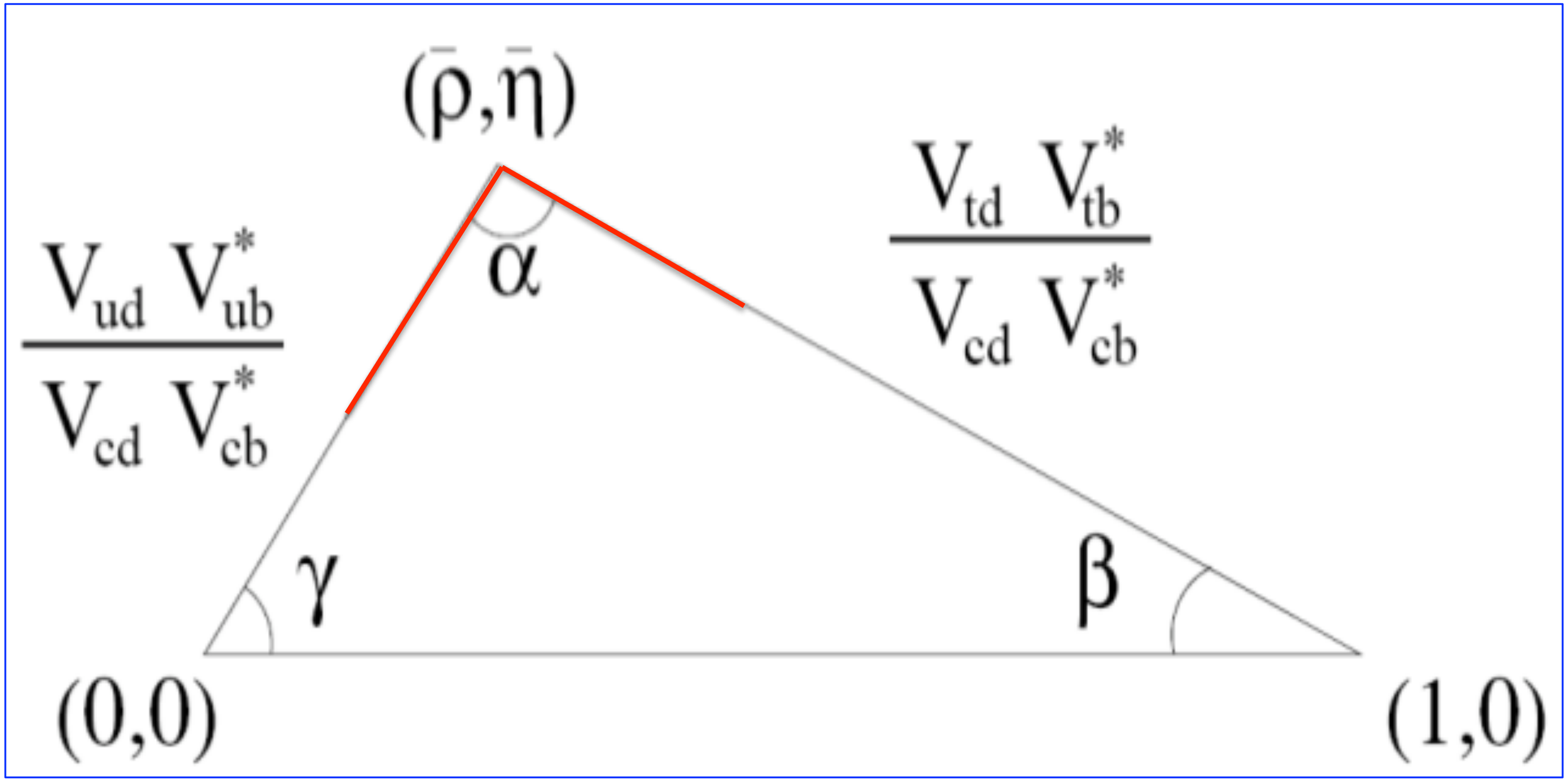
New Belle results this year:
$B^0 \to D^{*+}D^{*-}$ (ICHEP preliminary)
$B^0 \to J/\Psi\,\pi^0$: PRD **77**, 071101 (2008)

CP violation clearly established

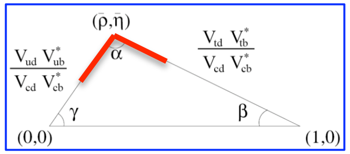


Good agreement with golden modes

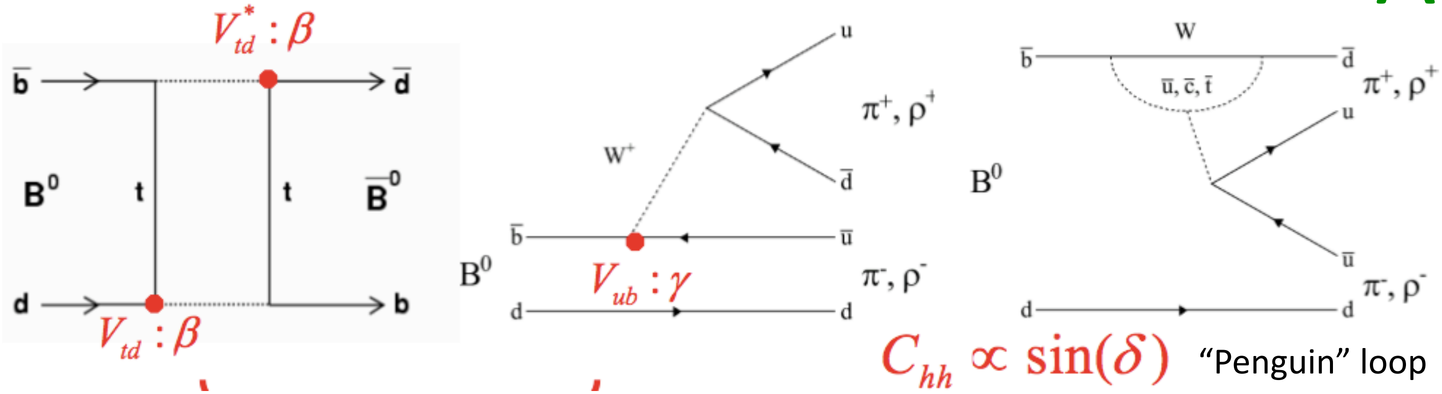
Angle α



$(\bar{\rho},\bar{\eta})$
$\frac{V_{td}\,V_{tb}^*}{V_{cd}\,V_{cb}^*}$
$\frac{V_{ud}\,V_{ub}^*}{V_{cd}\,V_{cb}^*}$
α
γ
β
(0,0)
(1,0)



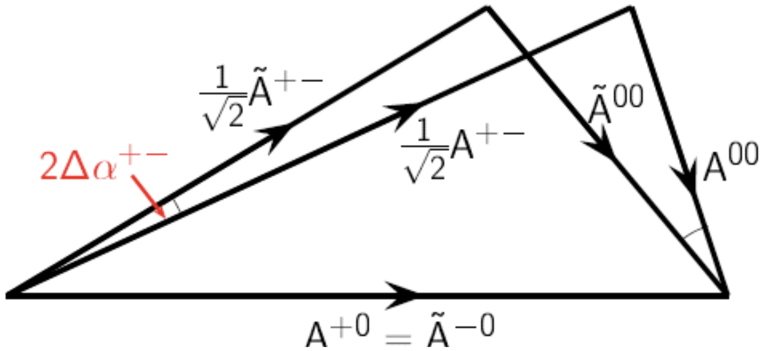
Angle α



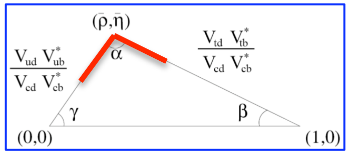
- Time-dependent CPV in b→u transitions
- Most useful modes:
    - B→ρρ, ππ, ρπ
- The interference of the box and tree diagrams would give exactly S=sin(2α), C=0 like the b→cc̄s giives S=sin(2β),C=0

$$S_{\text{eff}} = \sqrt{1 - C^2} \times \sin(2\alpha - 2\Delta\alpha)$$

- Problem: Penguin non negligible here, c
- Isospin analysis to measure Δα
    - 4-fold ambiguity in Δα
    - Small branching fractions



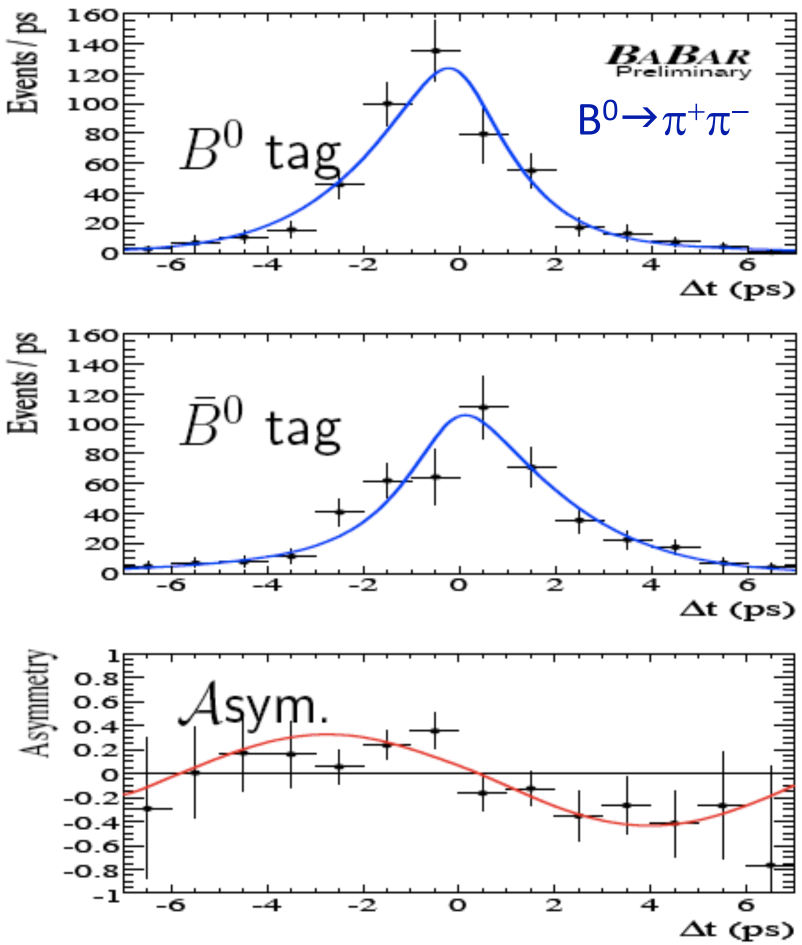
Gronau, London, PRL**65**, 3381 (1990)

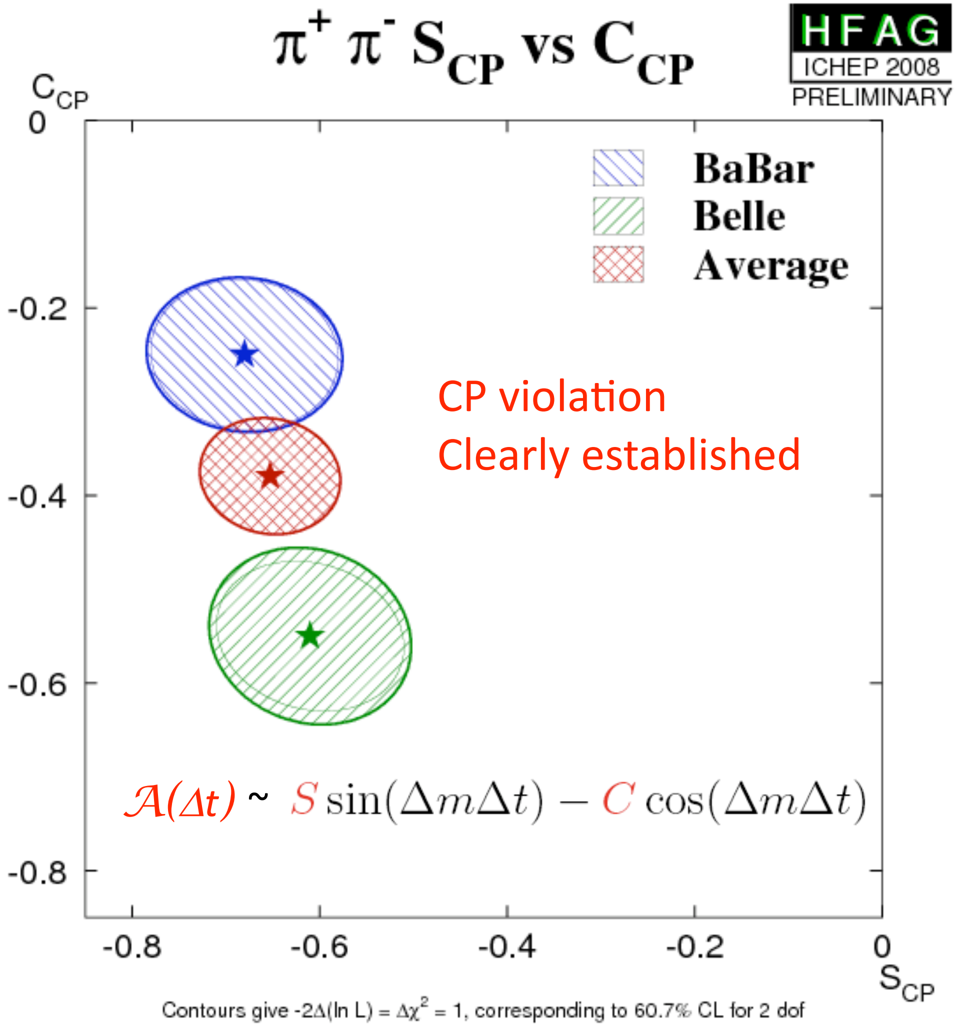


Angle α from $B\to\pi\pi$

Gritsan, ICHEP 2008

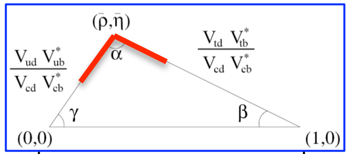
New from BaBar:
$B^0\to\pi^+\pi^-$, $\pi^0\pi^0$ (arXiv:0807:4226)





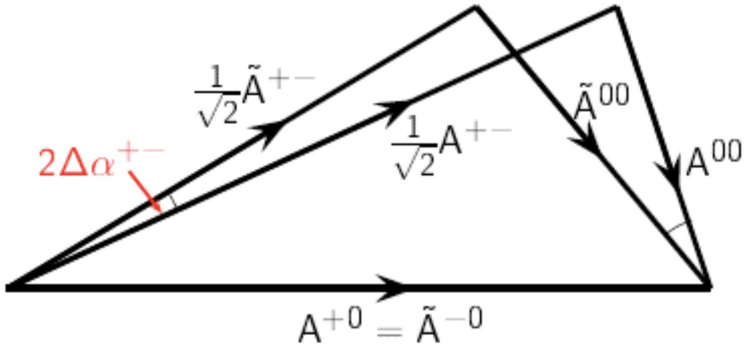
Angle α from B→ππ

Gritsan, ICHEP 2008

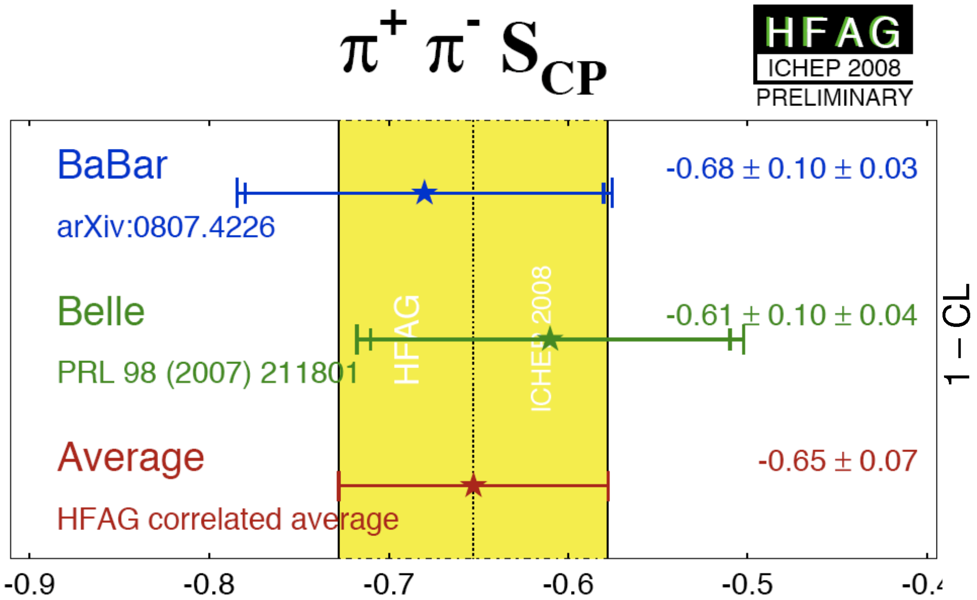


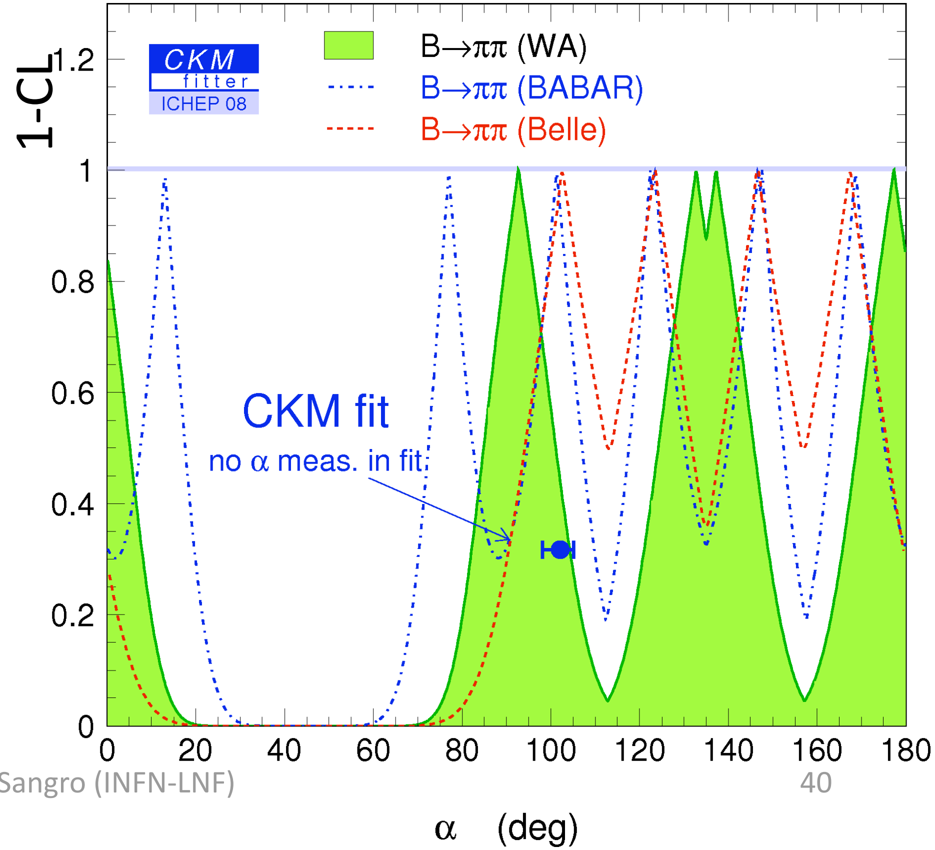
BABAR preliminary

	$\mathcal{B}(10^{-6})$	C
$\pi^+\pi^-$	$5.5 \pm 0.4 \pm 0.3$	$-0.25 \pm 0.08 \pm 0.02$
$\pi^+\pi^0$	$5.02 \pm 0.46 \pm 0.29$	–
$\pi^0\pi^0$	$1.83 \pm 0.21 \pm 0.13$	$-0.43 \pm 0.26 \pm 0.05$

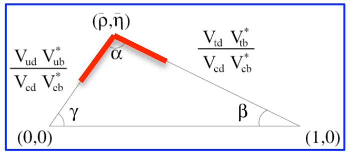


$\mathcal{B}(\pi^0\pi^0) \sim \mathcal{B}(\pi^+\pi^-)$: $\Delta\alpha$ could be large





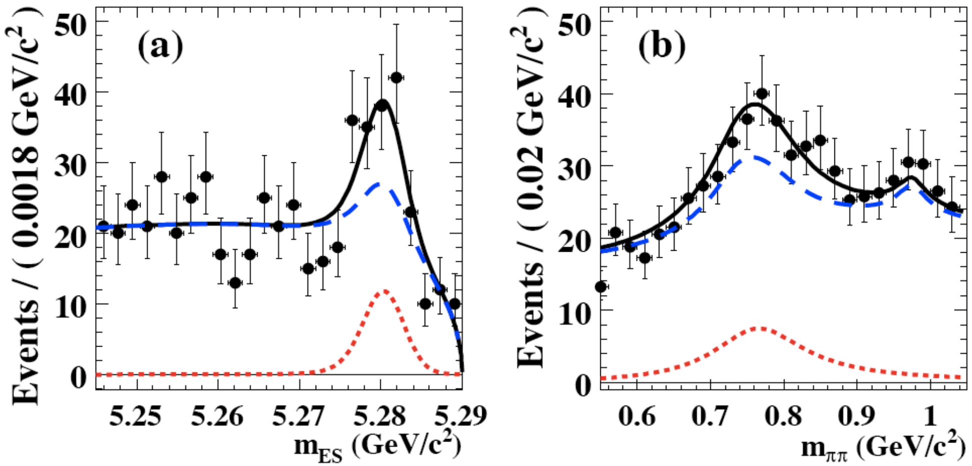
$\sigma(\alpha_{eff})$~4°, but $\sigma(\Delta\alpha)$<43°



Angle α from B→ρρ

Iwasaki, Gritsan, ICHEP 2008

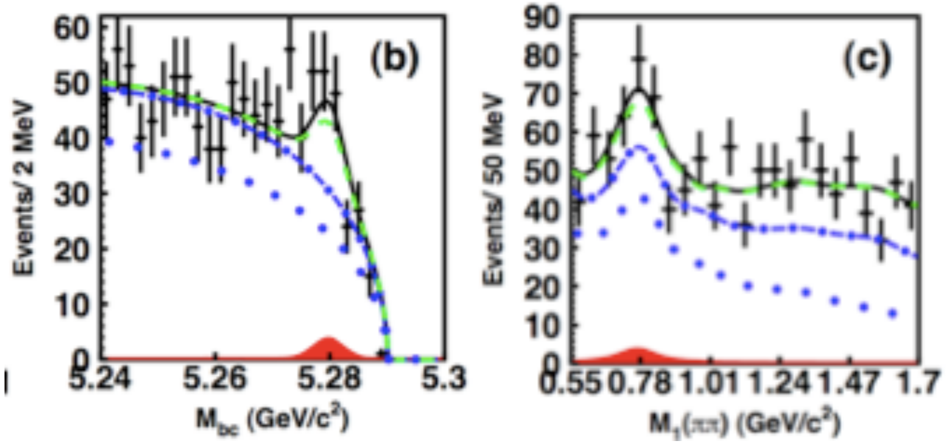
New from BaBar: $B^0 \to \rho^0\rho^0$ (arXiv:0807.4977)



$$\mathcal{B} = (0.92 \pm 0.32 \pm 0.14) \times 10^{-6}$$
$$f_L = 0.75^{+0.11}_{-0.14} \pm 0.04$$
$$S^{00} = +0.3 \pm 0.7 \pm 0.2$$
$$C^{00} = +0.2 \pm 0.8 \pm 0.3$$

3.1σ evidence for $\rho^0\rho^0$

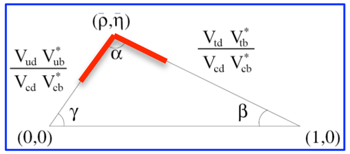
New from Belle: $B^0 \to \rho^0\rho^0$: $\mathcal{B} = (0.4 \pm 0.4 \pm 0.2) \times 10^{-6}$



World averages:

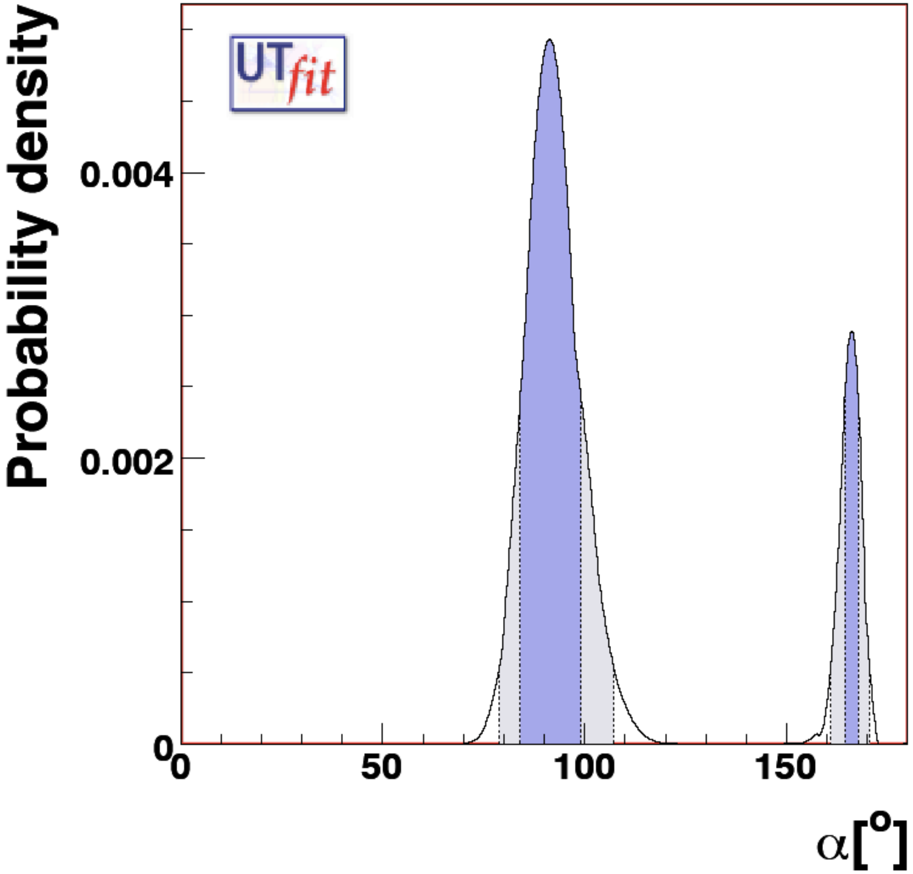
$$\mathcal{B}_{\rho 0 \rho 0} = (0.72 \pm 0.28) \times 10^{-6}$$
$$\mathcal{B}_{\rho+\rho-} = (24.2 \pm 3.2) \times 10^{-6}$$

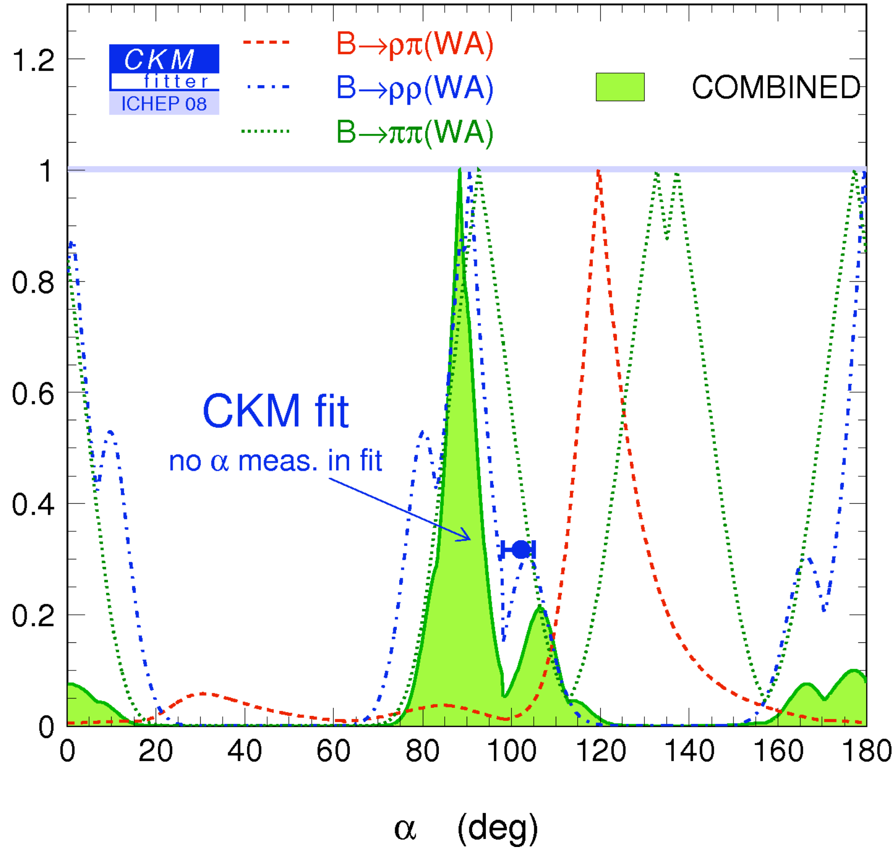
$\mathcal{B}(\rho^0\rho^0) \ll \mathcal{B}(\rho^+\rho^-)$



Summary of α

Pierini, Deschamps, ICHEP 2008

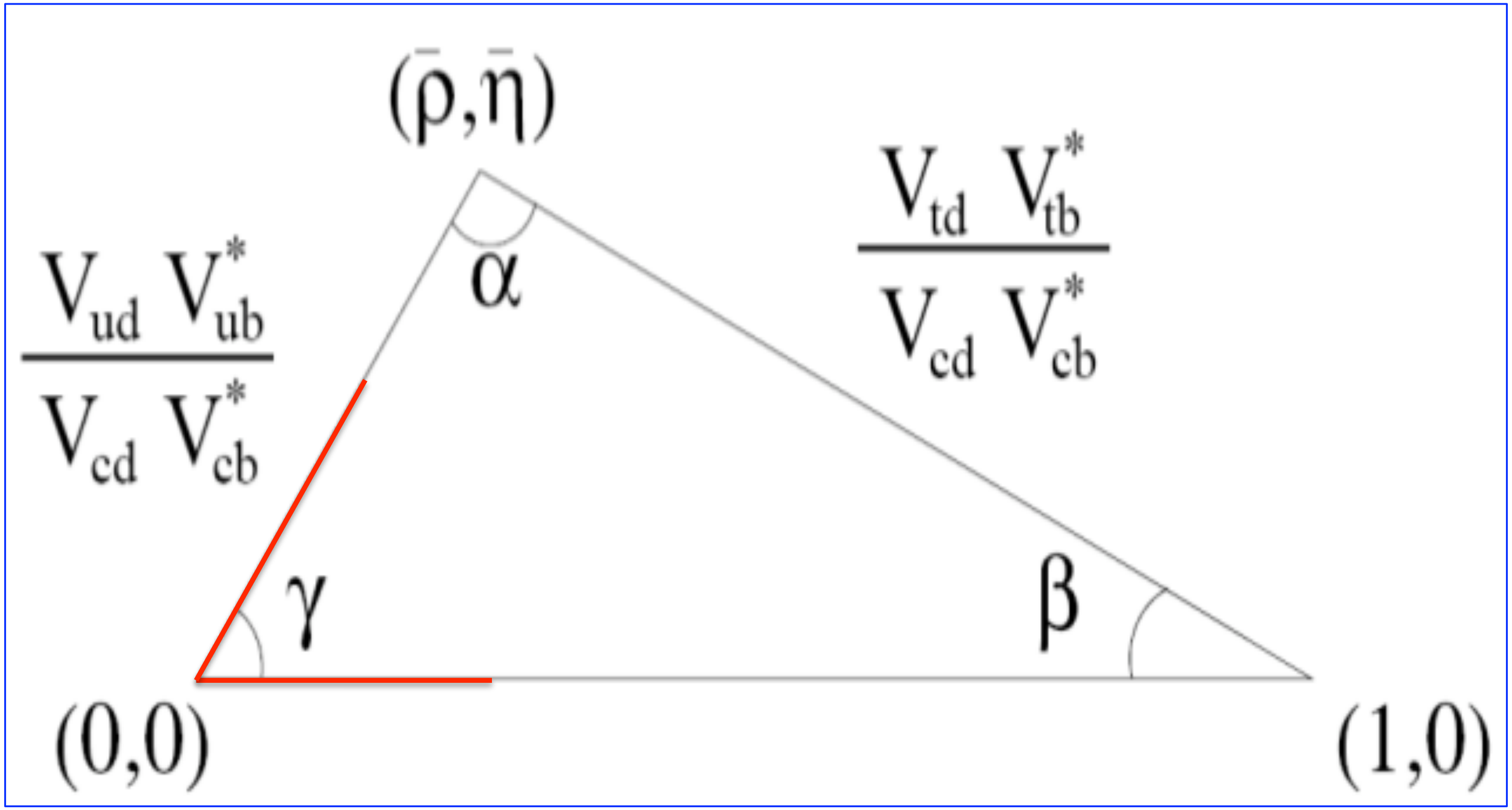




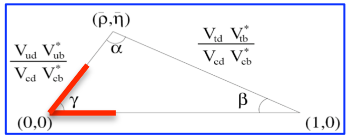
SM solution: $\alpha=(91\pm8)^o$

$\alpha \in [83.5\ ;\ 94.0]^o$ @ 68% CL

Angle γ



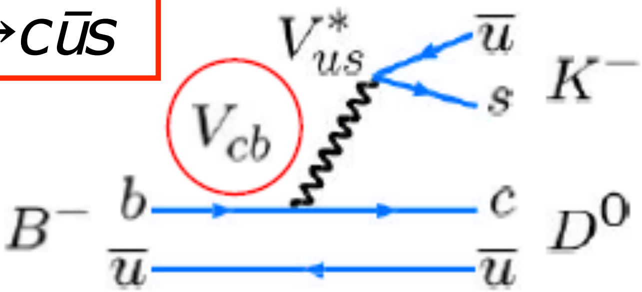
$(\bar{\rho},\bar{\eta})$
$\frac{V_{ud}\,V_{ub}^*}{V_{cd}\,V_{cb}^*}$
$\frac{V_{td}\,V_{tb}^*}{V_{cd}\,V_{cb}^*}$
α
γ
β
(0,0)
(1,0)



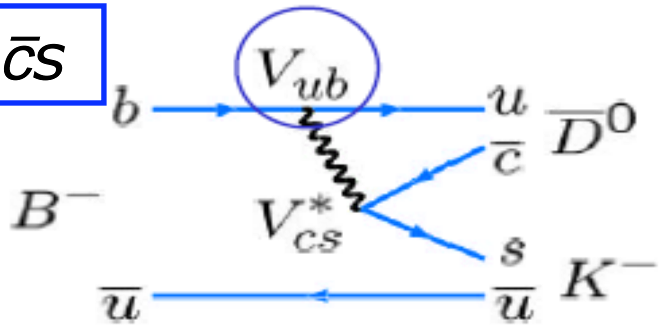
Angle γ

- Hardest UT angle to Measure
  - the phase of V_{ub}, and V_{ub} is small
- From direct CPV in the decay of charged *B*'s
  - Interfering tree amplitudes with *CP*-violating relative weak phase γ and *CP*-conserving relative strong phase δ
  - theoretically clean (i.e., no penguins involved)

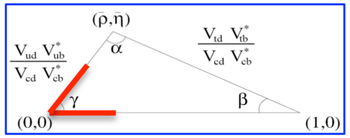
$b \to c\bar{u}s$



$b \to u\bar{c}s$



- Interference if $D^0/\bar{D}^0$ decay into identical final state
  - Dalitz plot (DP) analysis of 3-body decays, e.g., $D^0 \to K_s \pi\pi$ (GGSZ)
  - *CP*-eigenstate decay: Gronau-London-Wyler (GLW)
  - Doubly-Cabibbo-suppressed (DCS) decay: Atwood-Dunietz-Soni (ADS)

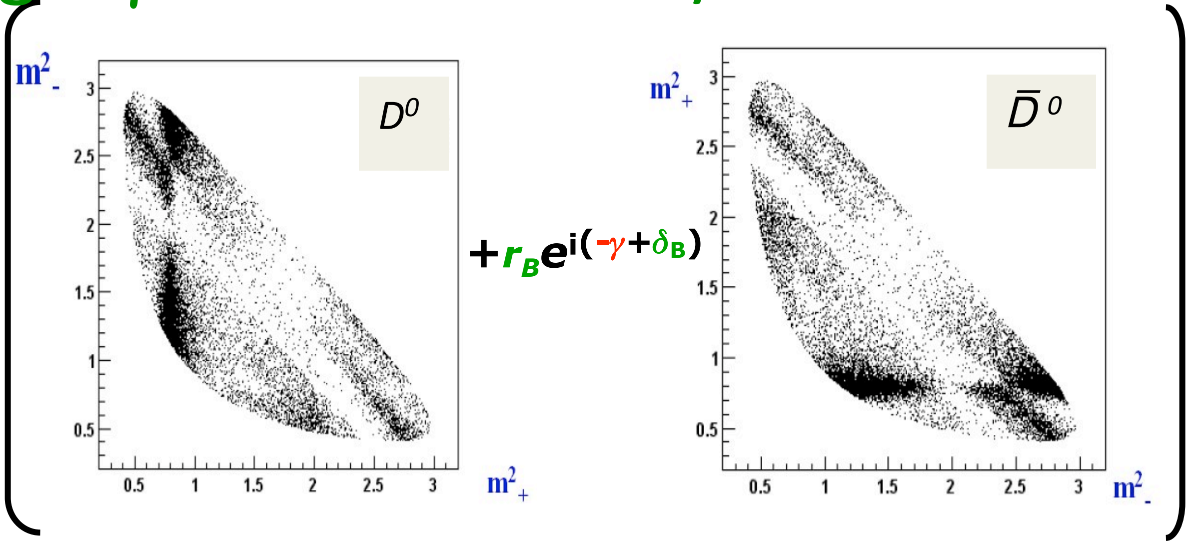


Angle γ : Dalitz Plot analysis of $B \to DK$

- The idea in pictures:

$A(B^-) = |A(B \to D^0 K^-)| \times$

$D^0 \to K_s \pi\pi$



- *CP*-conjugate B^- and B^+ decay amplitudes

$$A(B^-) = |A_B| \cdot \left[A_D(m_-^2, m_+^2) + r_B e^{-i\gamma} e^{i\delta_B} A_D(m_+^2, m_-^2)\right]$$

$$A(B^+) = |A_B| \cdot \left[A_D(m_+^2, m_-^2) + r_B e^{+i\gamma} e^{i\delta_B} A_D(m_-^2, m_+^2)\right]$$

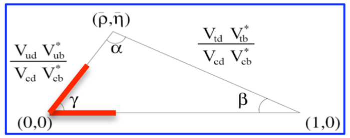
$m_\pm^2 = m(K_S \pi^\pm)^2$

Assume *D* decays conserve *CP*…

- $B^\pm$ Dalitz Plot distribution depends on γ, r_b and δ. It is convenient to write the Likelihood as a function of the cartesian coordinates x± and y±
  - Likelihood is Gaussian and unbiased

$$x_\pm = r_b \cos(\delta \pm \gamma);\ y_\pm = r_b \sin(\delta \pm \gamma)$$

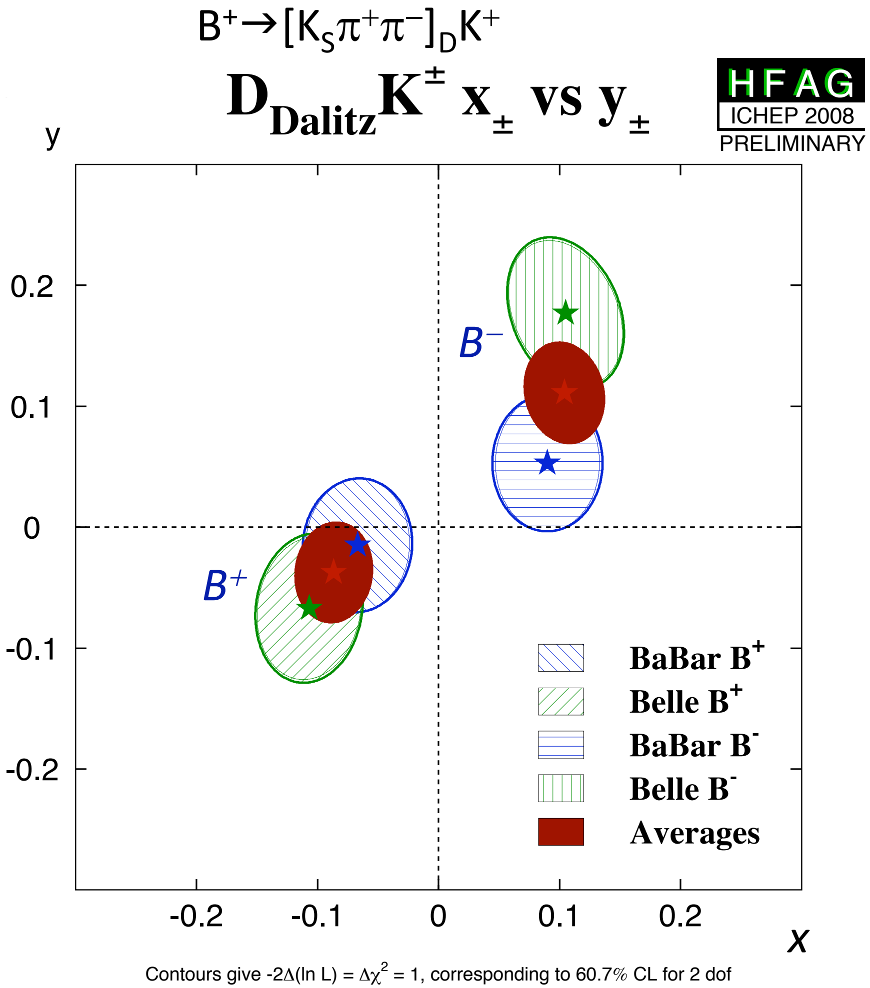
$$A(B^-) \propto |f_-|^2 + r_b^2 |f_+|^2 + 2x_- \mathrm{Re}(f_- f_+) + 2y_- \mathrm{Im}(f_- f_+)$$

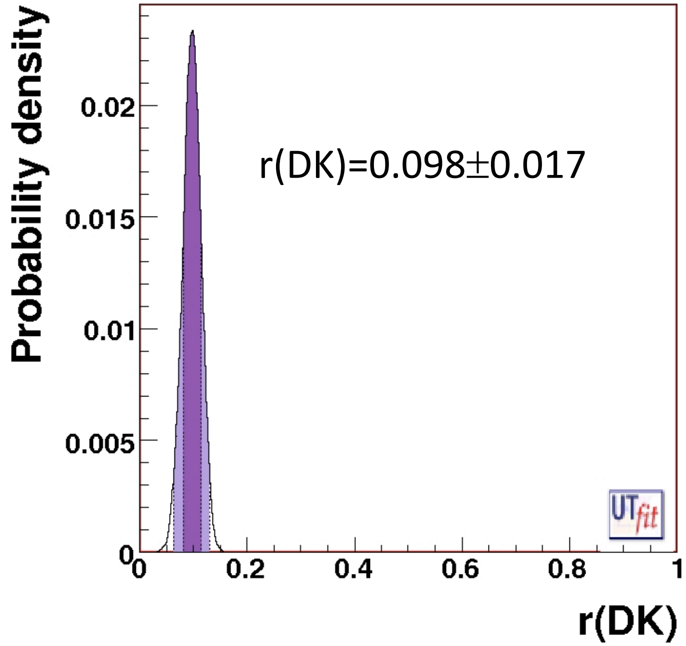


Kolomensky, ICHEP 2008

Angle γ : Dalitz Method Results

Quote "Cartesian" coefficients: $x_{\pm} = r_B \cos(\pm\gamma + \delta),\ y_{\pm} = r_B \sin(\pm\gamma + \delta)$

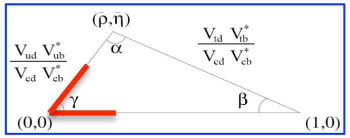




BaBar: $\gamma=(76\pm22\pm5\pm5)^o$

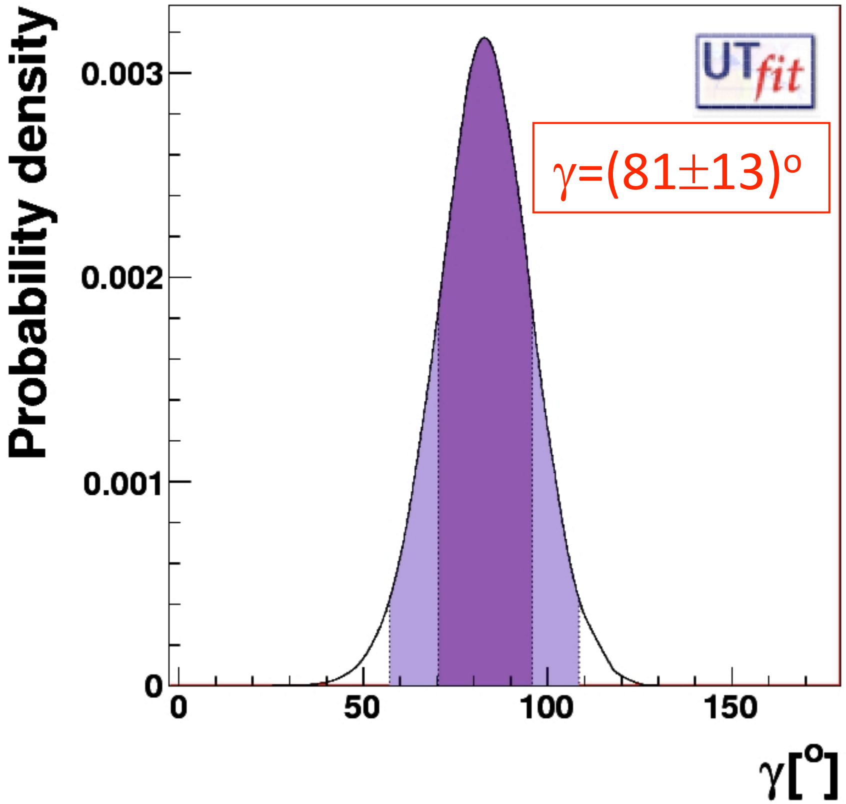
Belle: $\gamma=(76\pm12\pm4\pm9)^o$

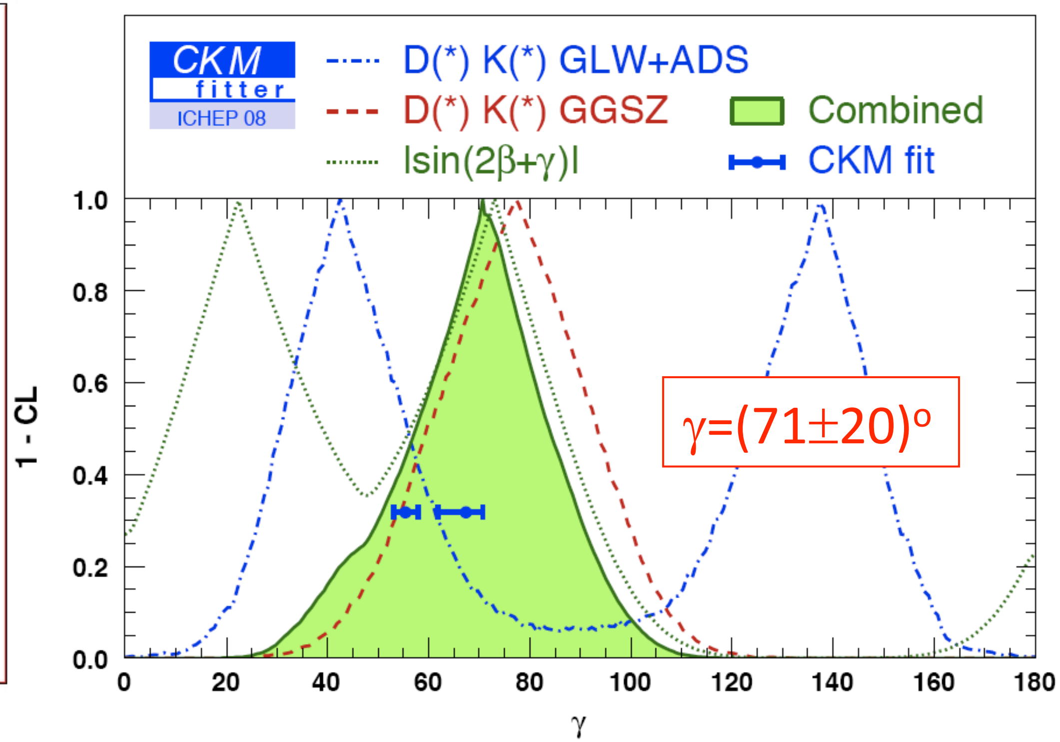
Evidence for CP violation in both Dalitz and GLW analyses !



Summary of γ

Pierini, Deschamps, ICHEP 2008

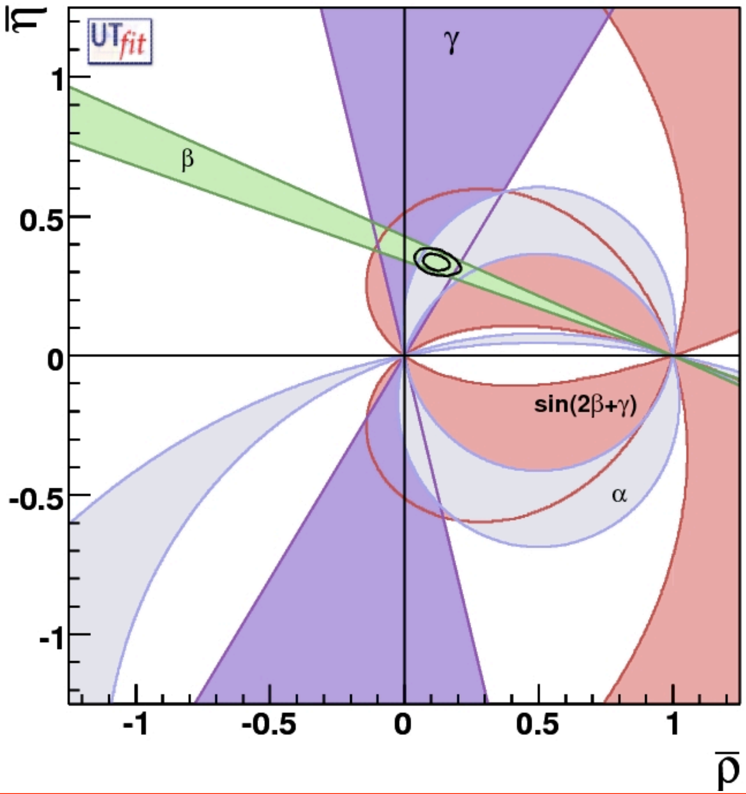


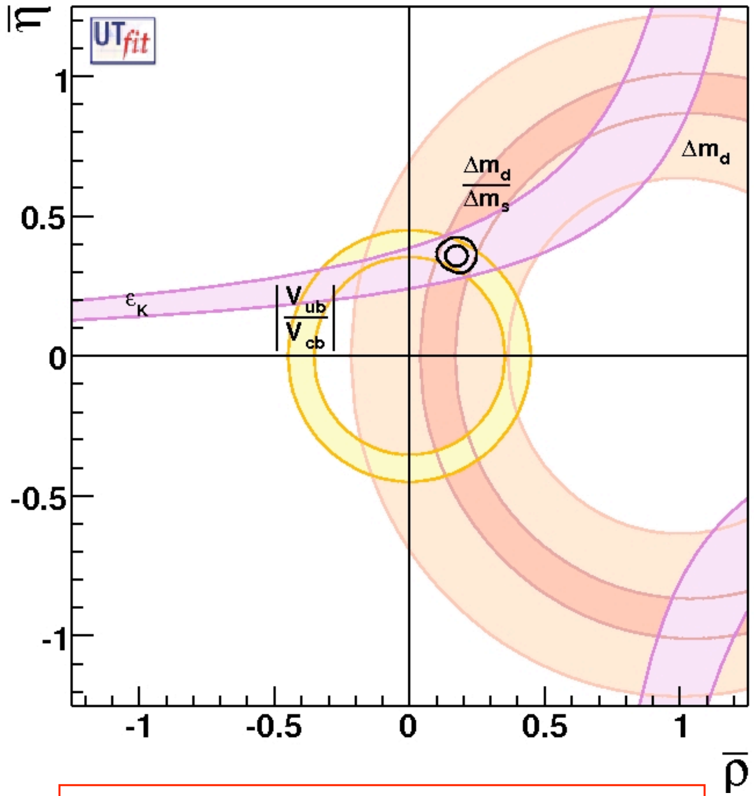


Difficult, statistics-limited measurements ! Combination of constraints: uncertainty of ~20° . Larger statistics needed (LHCb, SuperB)

UT Constraints: Angles vs Sides

Pierini, ICHEP 2008





Angle-only measurements (UTFit):

$\rho = 0.120 \pm 0.034$

$\eta = 0.335 \pm 0.020$

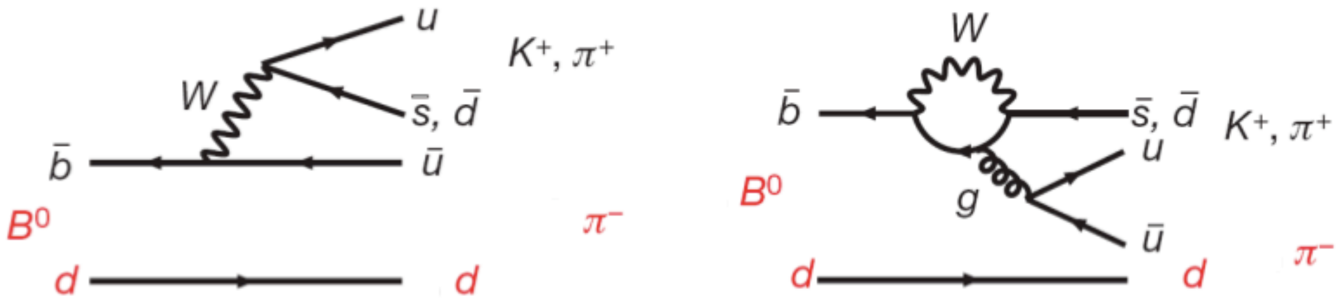
Other constraints (UTFit):

$\rho = 0.175 \pm 0.027$

$\eta = 0.360 \pm 0.023$

Direct CPV

- $B^0 \to K^\pm \pi^\mp$: Tree and gluonic penguin contributions

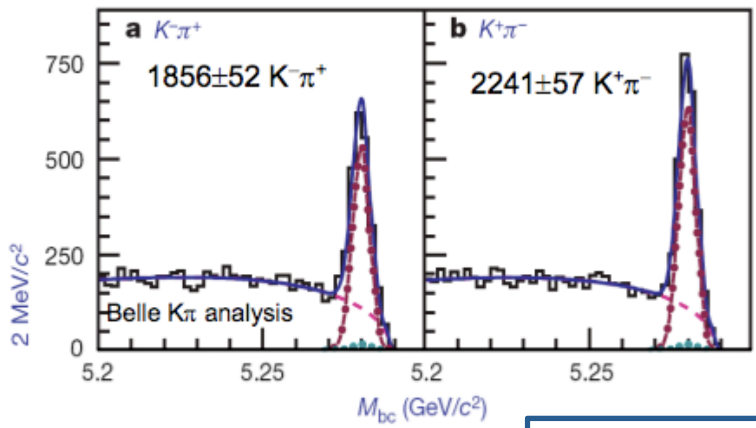


- Compute time integrated asymmetry

$$\mathcal{A}_{K^\pm\pi^\mp} \equiv \frac{N(\bar{B}^0 \to K^-\pi^+) - N(B^0 - K^+\pi^-)}{N(\bar{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)}$$

$$A_{K^\pm\pi^\mp} = -0.097 \pm 0.012$$

- Experimental results from Belle, BaBar, and CDF have significant weight in the world average of this CP violation parameter.
- Direct CP violation present in B decays.
- Unknown strong phase differences between amplitudes, means we can't use this to measure weak phases!



A. Bevan, HISS 2008

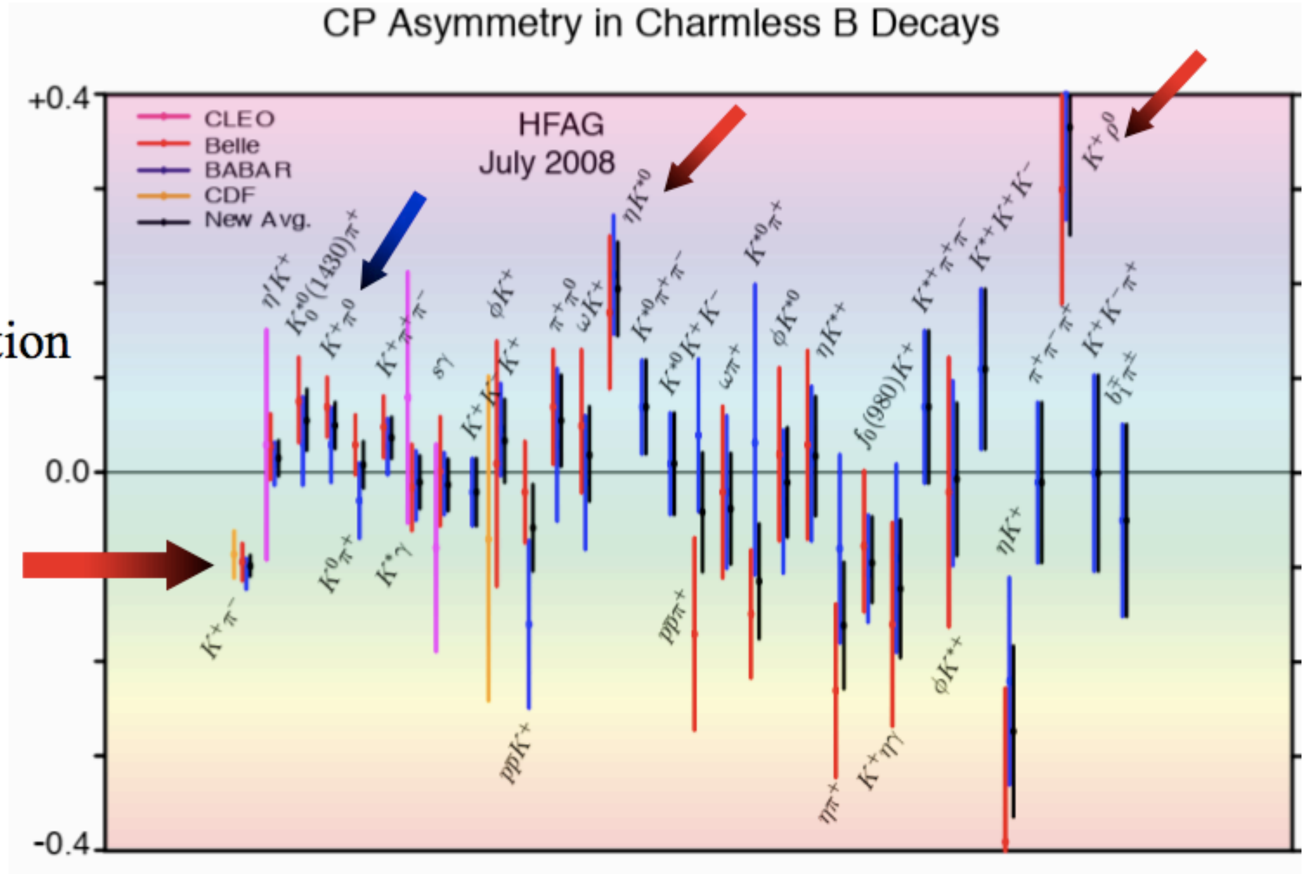
Direct CPV Searches

$$A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$$

$$A_{CP} = 0$$

$$= \text{no CP violation}$$

- Observed signal of direct CP violation in B meson decay

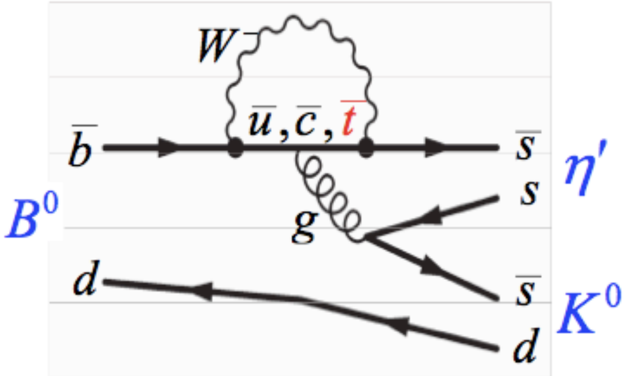


- This is a small sub-set of decays where we have searched for direct CP violation.
- 2 observed signals (> 5σ): $K^+\pi^-$ and $\pi^+\pi^-$; five possible effects (> 3σ): ρ^0K^+, ηK^{*0}, $\rho^+\pi^-$ $D^{(*)0}K^{(*)}$, and $D^0_{CP}K$.

A. Bevan, HISS 2008

New Physics Searches: $B \to \eta' K^0$

- Loop dominated b→s decay.



$$S_{\eta' K^0} = 0.60 \pm 0.07$$

$$C_{\eta' K^0} = -0.04 \pm 0.05$$

$$\Delta S_{\eta' K^0} = 0.07 \pm 0.07_{\text{exp}} \pm 0.01_{\text{theory}}$$

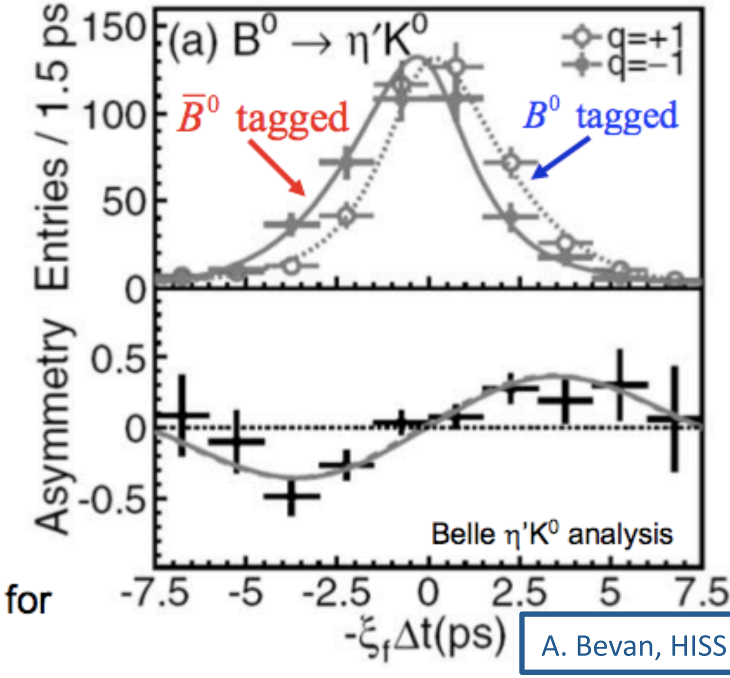
- CP violation has been established in this decay channel by the B factories.
- Need at least 50 ab^{-1} of data to do a precision search for NP at the level of current theoretical uncertainties.

- Possible to measure S and C for both

$$B^0 \to \eta' K^0_S \quad \text{(CP odd)}$$

$$B^0 \to \eta' K^0_L \quad \text{(CP even)}$$

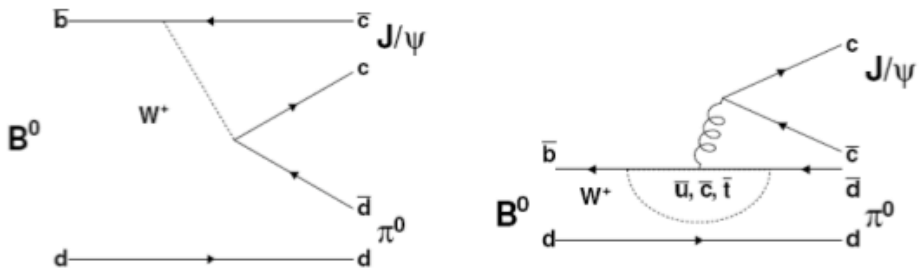
- These asymmetries can be compared with the Charmonium reference measurement to calculate ΔS.



A. Bevan, HISS 2008

New Physics Searches: $B^0 \rightarrow J/\psi\pi^0$

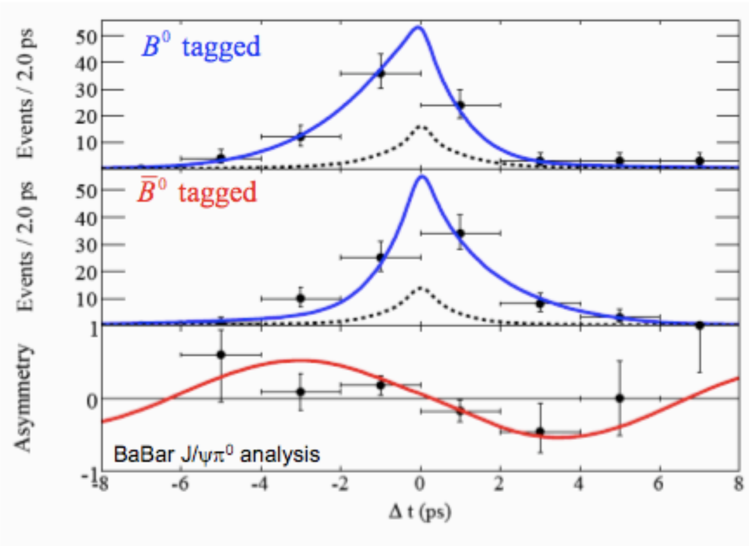
- Tree and penguin contributions: can be sensitive to NP.
- Alternatively, can be used to constrain SM uncertainties in the Charmonium β measurement. M. Ciuchini, M. Pierini, L. Silvestrini, **95**, 221804 (2005).



- CP even final state:

$$S^{Tree}_{J/\psi\pi^0} = -S_{c\bar{c}s}$$

- CP violation observed in this decay.



$$S_{J/\psi\pi^0} = -0.93 \pm 0.15$$

$$C_{J/\psi\pi^0} = -0.10 \pm 0.13$$

$$\Delta S_{J/\psi\pi^0} = 0.23 \pm 0.15_{exp}$$

- Require a dataset of ~$220 ab^{-1}$ to make a 1% ΔS measurement in this channel.

A. Bevan, HISS 2008

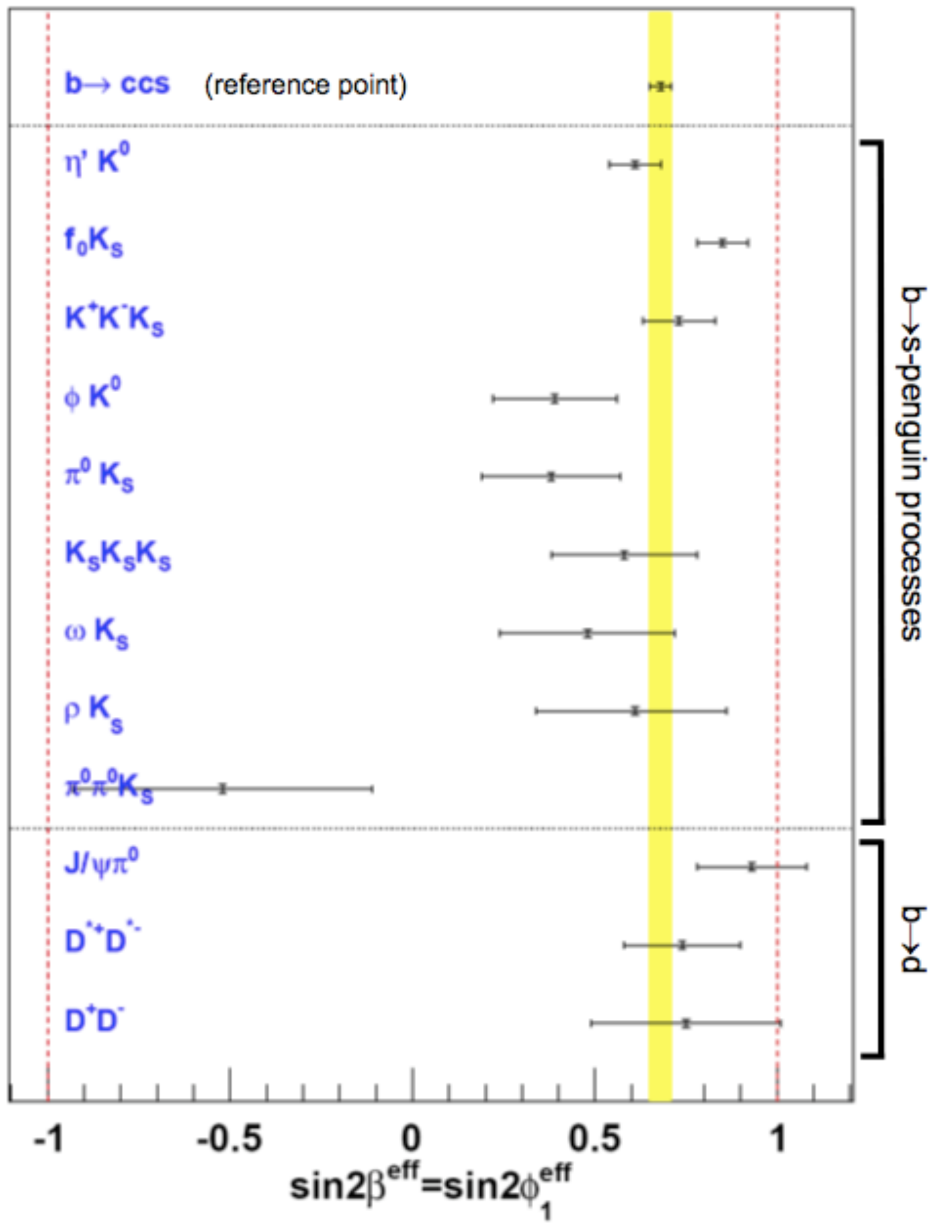
Summary of ΔS

•Comparing sin2β in different physical processes, we see good agreement with the b→cc̄s reference point.

• We need at least ≈50 ab^{-1} to start performing measurements with comparable theoretical and experimental errors in the b→s penguin processes

• We need ≈220 ab^{-1} to achieve the same in b→d.

•This kind of comparison could be done also for α and γ once a precision measurement of one mode is made



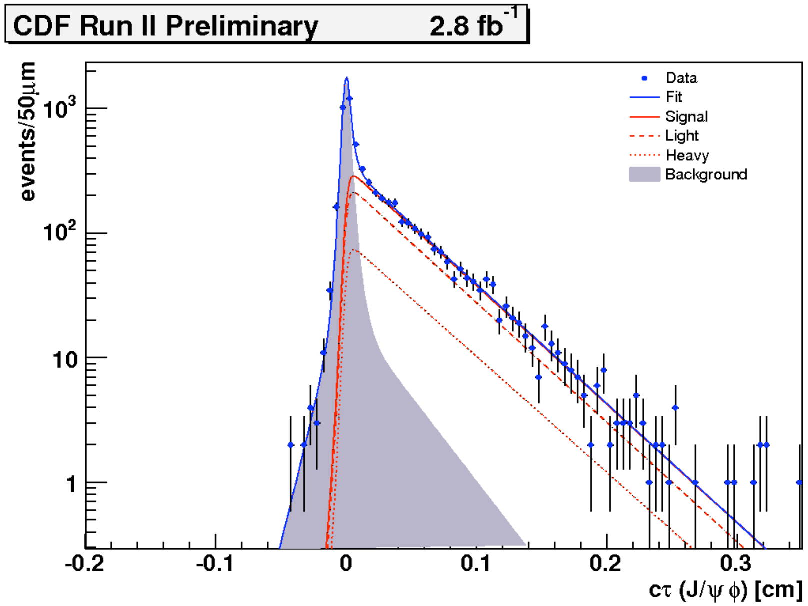
CPV in B_s Decays

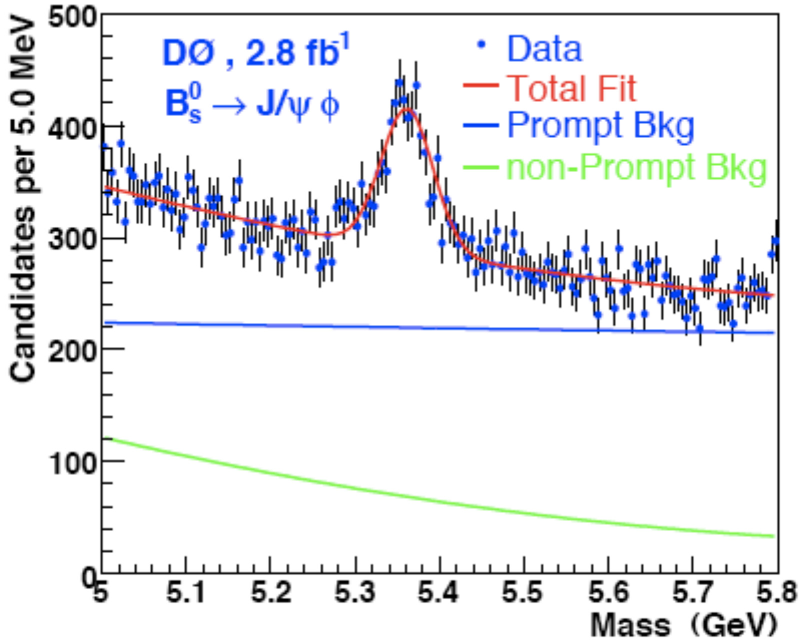
Tonelli, Ellison, ICHEP 2008

- CPV in $B_s \to J/\Psi\phi$ measures the phase of B_s mixing amplitude

$$\beta_s \equiv \arg\left[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)\right]$$

  - Predicted to be nearly zero in the Standard Model
  - New Physics may enter through mixing box
  - Angular analysis determines fractions of CP-odd and CP-even eigenstates
  - Simultaneous fit for β_s and $\Delta\Gamma_s$

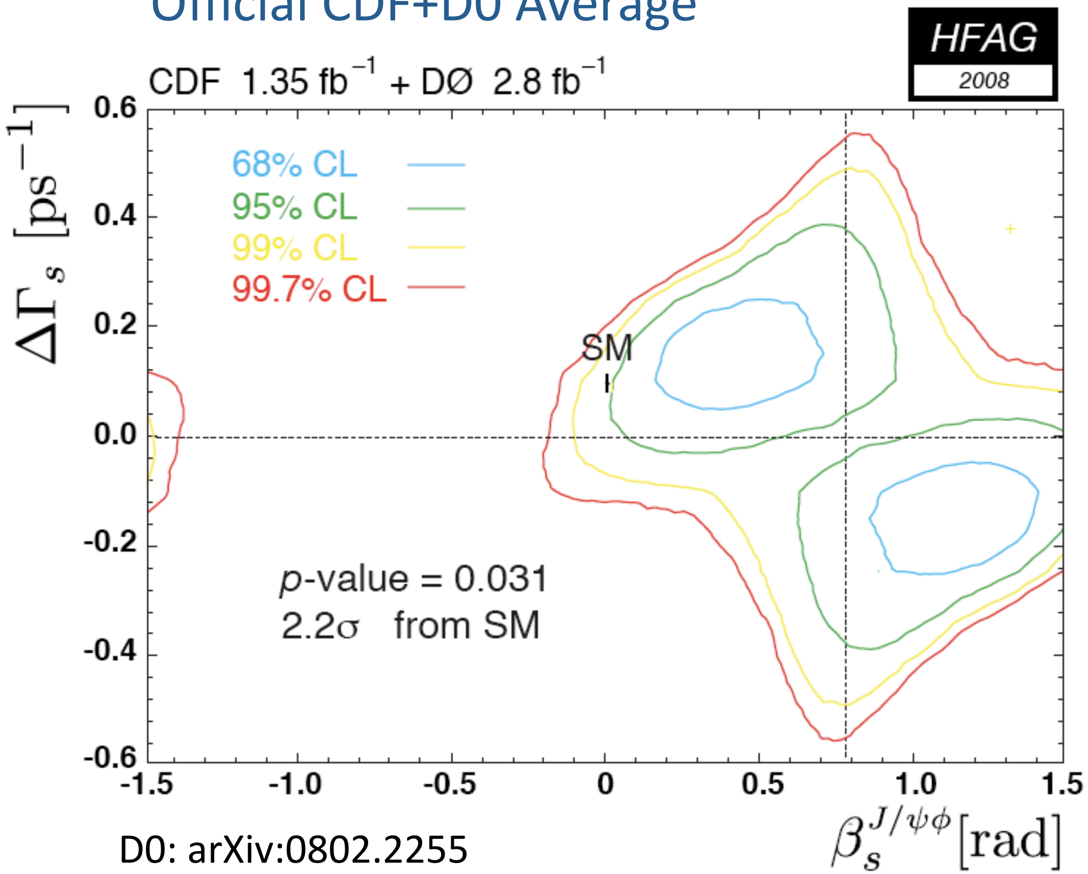




β_s Results

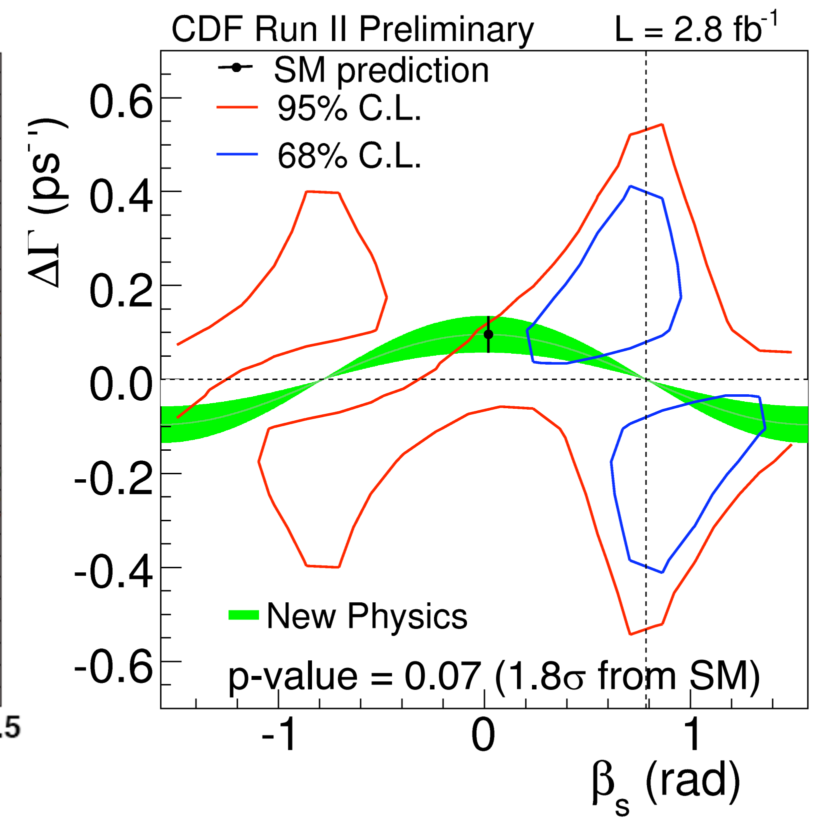
Tonelli, Ellison, ICHEP 2008

Official CDF+D0 Average



D0: arXiv:0802.2255
CDF: PRL**100**, 161802 (2008)

➔ New CDF results

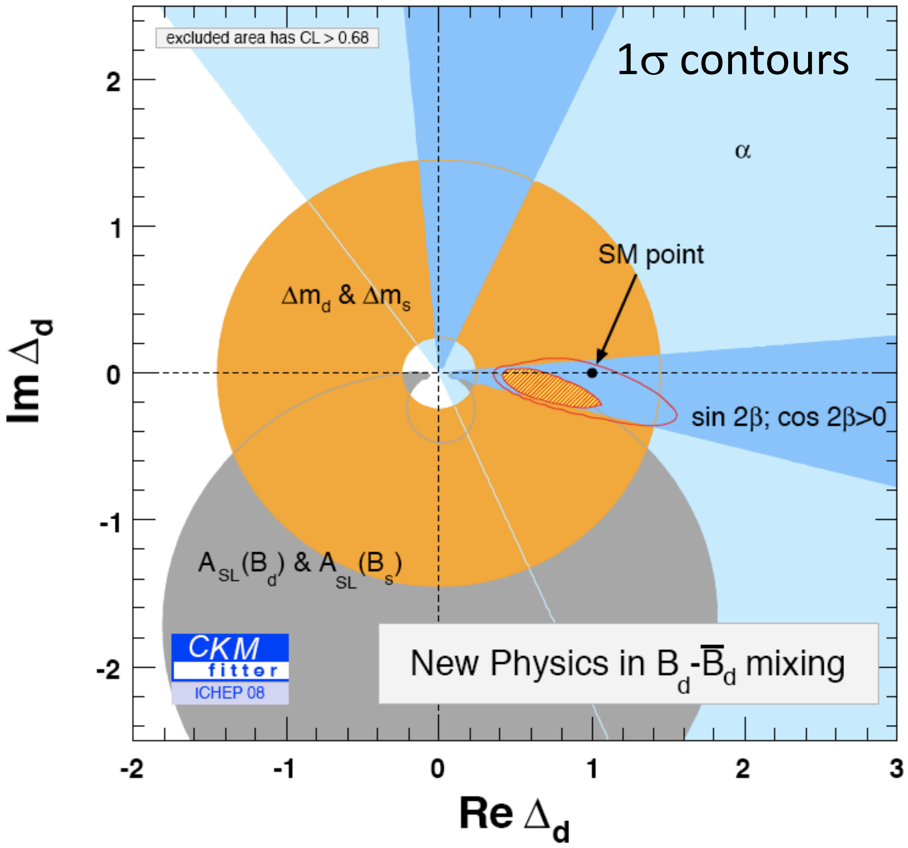


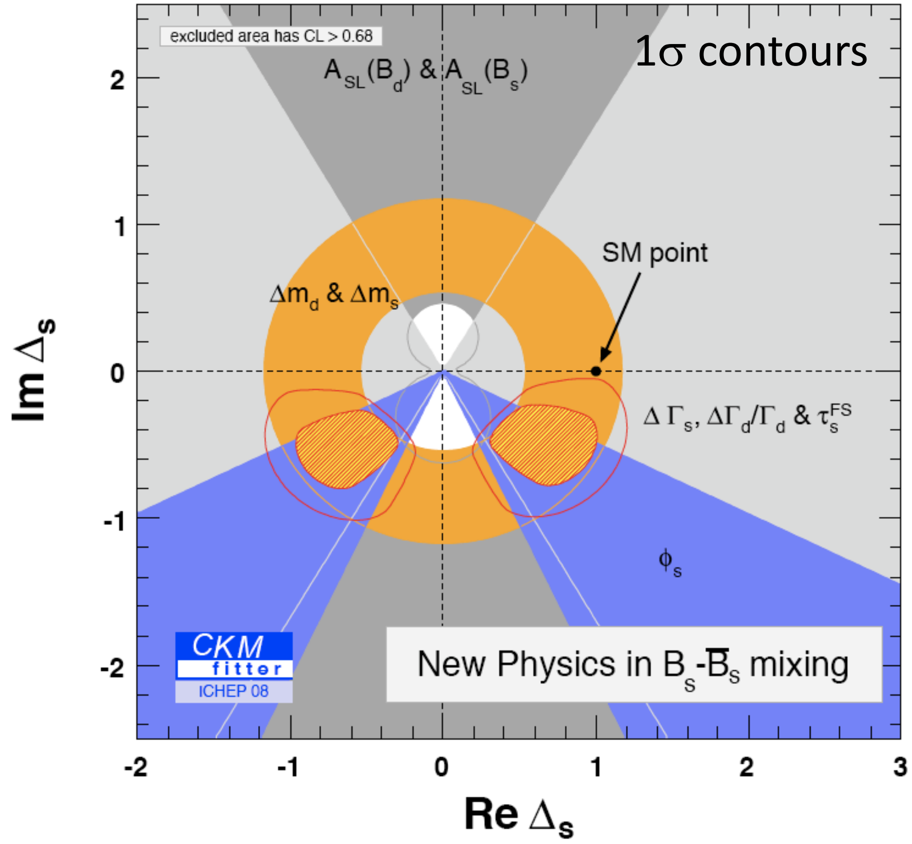
Is this a hint of new physics in B_s mixing ?

More data from the Tevatron coming

New Physics Constraints in Loops

Deschamps, ICHEP 2008





Agreement with SM at 1-2σ level

Largest deviations in β_s and $B\rightarrow\tau\nu$

$$\left\langle B_q^0 \left| M_{12}^{SM+NP} \right| \overline{B}_q^0 \right\rangle \equiv \Delta_q^{NP} \cdot \left\langle B_q^0 \left| M_{12}^{SM} \right| \overline{B}_q^0 \right\rangle$$

Summary

- High-precision measurements at the "Flavour-factories" and Tevatron over the last few years have tested the CKM mechanism to an unprecedented level

$$\sigma(\bar{\rho}) \sim 16\%, \quad \sigma(\bar{\eta}) \sim 4.7\%$$

- There is an overall excellent agreement between sides and angles of the Unitarity Triangle leaving little room for new physics at the present level of precision
- Many measurement are still statistics limited (i.e. UT angles)
- First measurements of CPV in B_s decays hint at SM deviation
- Need for more precise measurements to search for NP effect leading to deviations from the CKM model

2008 Nobel Prize to KM well deserved!

but Cabibbo?

Outlook

- Final dataset from BaBar (~500M B decays)
- Belle continues operations to O(1000M decays)
- Expect soon to ≈double the dataset at the Tevatron
- Higher precision is around the corner
  - Final, combined B Factory and Tevatron datasets (2010)
  - LHCb (2009-2010)
  - KLOE approved for one extra year run at DAFNE, total ≈ ×4 present data (2010)
  - Very rare, theoretically clean, K decays are "golden" probes for NP searches:
    - NA62 to measure $K^+ \rightarrow \pi^+ \nu\nu$; approved at CERN (~2012)
    - Measure $K_L \rightarrow \pi^0 \nu\nu$; proposal in Japan (E14 @ J-PARC) (~2015)
- In the planning stages: Super B factories in Italy and Japan (2015) ⇨ see G. Finocchiaro's talk